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United States
Department of
Agriculture

Forest Service

Forest Pest
Management

Davis, CA

Third Report

NATIONAL SPRAY MODEL ADVISORY COMMITTEE

FPM 92-10
July 1992

FPM 92-10
JULY 15, 1992

<u>Third Report</u>

National Spray Model Advisory Committee -

Notes of the Charlotte, NC Meeting June 23, 1992

Prepared by:

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Chairperson

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I. INTRODUCTION

The meeting was held at the Radisson Plaza Hotel, Charlotte, North Carolina, June 23, 1992 in conjunction with the International Summer Meeting of the American Society of Agricultural Engineers (ASAE). This scheduling provided for economies in travel as several members also had planned to attend the ASAE meeting.

A. **Attendees:**

Larry Barber	USDA Forest Service (R-8) Asheville, NC
Terry Biery*	USAF Reserve (Vienna, OH)
Jesus Cota	USDA Forest Service (WO/FPM) (Washington, DC)
Tom Curbishley	Continuum Dynamics (Princeton, NJ)
Harold Flake*	USDA Forest Service (R-8) (Atlanta, GA)
Eric Franz*	USDA-ARS (College Station, TX)
Kevin Howard	USDA-ARS (Stoneville, MS)
Steve Knight*	USDA-APHIS-PPQ (Hyattsville, MD)
Alex Mangini	USDA Forest Service (R-8) (Pineville, LA)
Dave Miller*	University of Connecticut (Storrs, CT)
Harold Thistle*	Missoula Technology Development Center (Missoula, MT)
Pat Skyler*	USDA Forest Service (WO/FPM) (Davis, CA)
Bill Steinke*	University of California (Davis, CA)

Milt Teske*	Continuum Dynamics, Inc. (Princeton, NJ)
Dave Valcore*	Dow Elanco Spray Drift Task Force (Indianapolis, IN)
Jeff Witcosky*	USDA Forest Service (R-8) (Harrisburg, VA)
Dave Whiteman*	Battelle NW Labs (Richland, WA)
Al Womac*	USDA-ARS (Stoneville, MS)
Jack Barry* (Chairperson)	USDA Forest Service (WO/FPM) (Davis, CA)

Notes: Asterisk (*) indicates committee member
Milt Teske is an ad hoc member

B. Purpose of Committee/Meeting

The purpose of the committee is to share information and to identify needs related to the FSCBG and AGDISP pesticide spray computer models, and list priorities related to development, enhancement, evaluation, validation, training and technology transfer. Identified needs are sent to the USDA Forest Service (Forest Service), Director of Forest Pest Management for program and funding considerations. Equally the recommendations are also used by other public and private organizations for consideration in managing their pesticide application R&D program. The Charlotte meeting, as others that preceded it, provided a forum for constituents to express their needs and to state where emphasis should be placed in advancing the pesticide application models and to encourage cooperation and partnerships.

C. Retrospective and Future Direction

The three primary uses of the models are for conducting research, establishing regulatory criteria, and planning operational control projects. As the FSCBG and AGDISP models have matured their role in these primary uses has become defined and better understood by the user community. This committee has furthered the use and enhancement of the models by bringing together individuals and organizations who have a need for this technology. The USDA Forest Service and U.S. Army have in the past provided the primary leadership and funding to support the models.

The interest and need for the models have expanded to other Federal, State, academia, industry, and to international users as demonstrated by the Spray Drift Task Force (SDTF), Canada, New Zealand, and Australia. As the interest of committee members and others focuses on future model uses and specific needs it is my expectation that resources from other than the Forest Service and U.S. Army, will become available and directed to address needs identified by this committee. I also believe we will see more partnerships in conducting field research of the models.

While the Forest Service has plans to continue the development and evaluation of the FSCBG model, the Forest Service position is that further development and enhancements of the model should be shared by the entity that has the specific need - whether it be model enhancement, validation, evaluation, or enhancement. The Model User Group, established by the Forest Service through a memorandum of understanding with Continuum Dynamics, Inc., and the National Spray Model Advisory Committee are appropriate coordination points for model work of the nature described above. Your support of the model and this committee is very much appreciated. We need your continued participation to further FSCBG in research, regulatory, and operational uses.

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II. DISCUSSION

The discussion as presented herein are remarks by attendees and/or a summary of their work. Some attendees provided a written summary which is enclosed in the Appendices.

A. Attendees Remarks and Reports

Larry Barber

- Conducting ULV tests of Bt in coniferous seed orchards.
- Noted serious problem in Rhodamine WT dye degradation - 50% in an hour.
- Conducting a study with Alex Mangini, Bob Sanderson, and Scott Cameron on a project to simulate aerial spraying with a ground sprayer. FSCBG model is being used for calibration of simulator.

Jack Barry

- Need to incorporate near-canopy stability parameterization into model.
- Need ASAE standards for atomizer characterization in wind tunnels. Bill Steinke is pursuing this suggestion from last year's meeting.
- A symposium titled "Application Technology for Microbials, Pheromones, and other Biorational Pest Control Agents" has been approval by the American Chemical Society (ACS). Location of the symposium is being proposed for the national ACS meeting in Chicago, fall 1993.

- In characterizing forest canopies where do we begin and end? Need someone (forester) with experience to come up with five class types of forest canopies to characterize. Need sub-committee to get this started. Milt knows what model needs. Jeff Witcosky, with some help, agreed to chair a canopy characterization sub-committee with charge to address this issue and give recommendations.

- Need to account for drops <33 um in models. Suspect that small drops influence model when predicting number of drops or biological colony forming units. Data may be available to make evaluation.

- Need to revisit aircraft vortex strength and duration vs wind speed and direction and determine if model tuning is needed.

- Need to determine appropriate methods, instruments, and measurement frequencies for characterizing atmospheric conditions on various field types of studies.

- Expressed concern and need for field sampler quality control methods, especially when conducting tests for model evaluation. Considerations are sampler collection efficiency, threshold, background levels and contamination. Use of Bt as a drift tracer is a new approach to the Forest Service. Spreading of droplets on Kromekote cards is another problem to those who rely upon Kromekote cards. Slight changes in spread factors can make significant differences in estimates of mass volume deposition per unit area. For this reason mass/volume calculated from Kromekote cards should never be used solely to judge spray prediction models. It is suggested that drops/unit area from cards or other tracer techniques be used.

- Coordinated a Bt drift study in cooperation with FS Intermountain Region and U.S. Army in Utah. FSCBG model predictions were compared to field data. See ASAE Paper 921085 in Appendix.

<u>Terry Biery</u>

- Continued interest in drift and cloud touchdown as function of aircraft release height, and tables with FSCBG prediction of maximum mosquito kill. (FSCBG 4.0 can provide this information).

- Using FSCBG effectively for upwind offset for C-130.

- Noted excellent correlation of FSCBG predictions to field data (see following table). Used oil sensitive cards and counted number of drop stains/cm^2. Release height was 200 feet with 22 um (VDM) drops.

<u>Jesus Cota</u>

- From an administrative standpoint it is valuable and important that the group provides input as to what is important for funding - also important as a technical group that we co-ordinate and cooperate in technical development.

- Committee recommendations to Director, Forest Pest Management may be changed from September 1 to later in September. This was in response to some who would like national steering committees to be held early September.

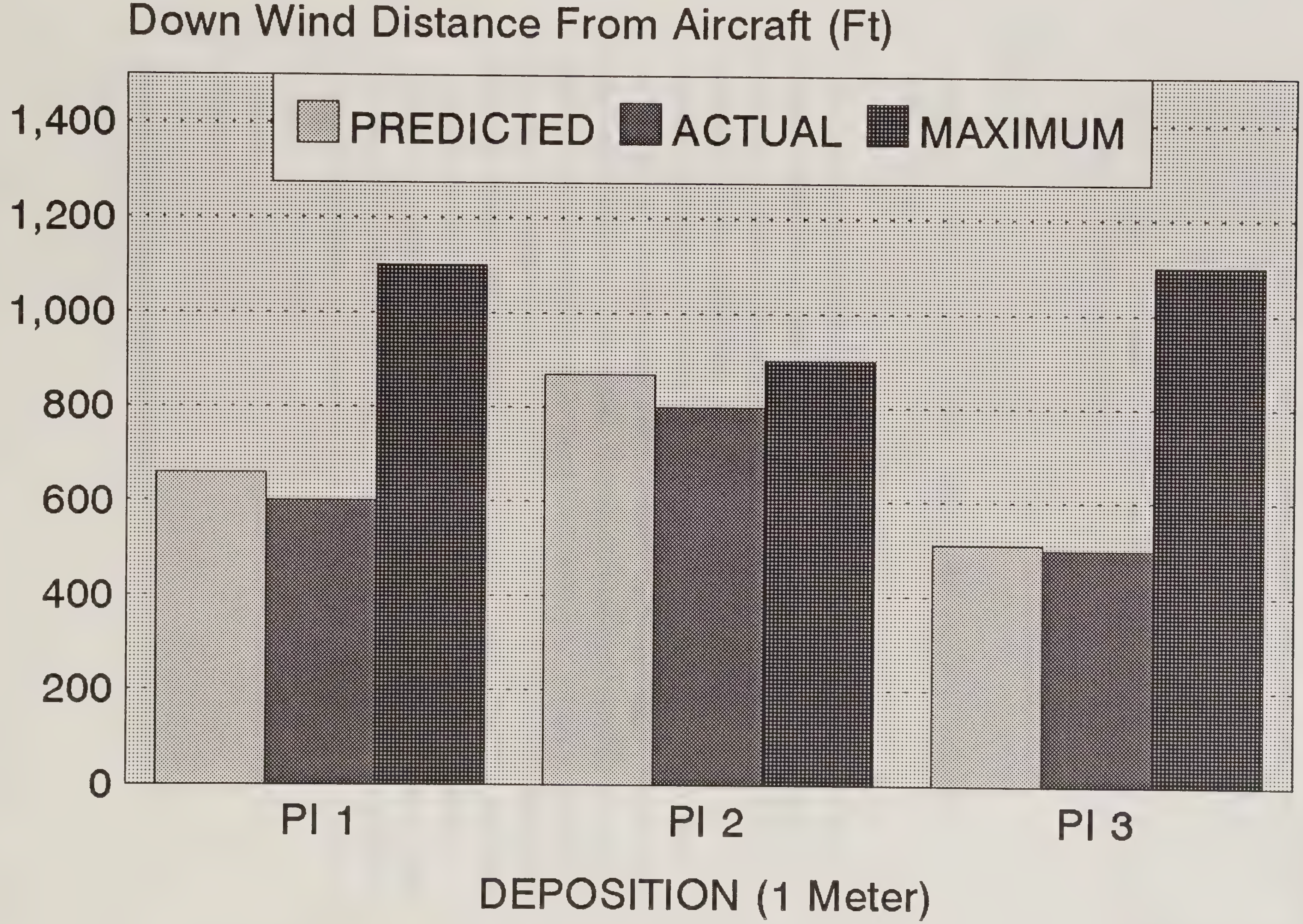
- Emphasized that this and other national steering committees established by Jim Space also serve as an important way to promote cooperation and partnerships.

<u>Harold Flake</u>

- Reported failure to control more than 50% of gypsy moth in DC-3 treated blocks is attributed to too wide of swath width. AGDISP confirmed that 300 foot swath is too wide. (Might too high a release height also be a problem?)

- AGDISP has been accepted and is being used.

FSCBG FIELD EVALUATIONS FOR DRIFT "OFF-SET" USING C-130 AIRCRAFT



Steve Knight

- Interested in FSCBG for use in urban spraying, complex terrain spraying, and total accountancy. Noted APHIS-PPQ urgency in knowing what models will do.

- Suggested that findings of Milt Teske's FSCBG sensitivity study be added to FSCBG user manual.

Alex Mangini

- Doing an orchard spray project with cooperators to simulate aerial spray.

- This is a Forest Pest Management Technology Development Project being conducted by Scott Cameron, Texas Forest Service, Bob Sanderson, New Mexico State University, Larry Barber and Alex Mangini, Forest Pest Management. Summary of progress: deposition and drift data were collected on large orchard trees last June at the Erambert Seed Orchard in Mississippi. Data from smaller trees were collected in May of this year (1992) at the Boise Cascade Evans Seed Orchard in Louisiana. These data will be used in testing the ground-based simulation sprayer (GBS) and will be used to compare with model predictions. The GBS has been constructed and Scott is using it to conduct efficacy tests on tip moth in small pine trees. The sprayer is being compared with conventional ground spraying. The cooperators will get together later this summer to complete the data analysis and plan further testing of the GBS.

Dave Miller

- Need a 5-year plan for characterizing forest canopies to obtain input for FSCBG.

Interested in [illegible] for use in [illegible] grazing [illegible] surveys, and [illegible] recommend[illegible]. [illegible] shown in the [illegible].

Suggested that [illegible] of [illegible] be added to [illegible].

[illegible]

Doing [illegible] project with [illegible]

This is a [illegible] Pest Management [illegible] Department [illegible] being conducted [illegible], Forest Service, [illegible] New Mexico State University [illegible]. [illegible] and [illegible] Department of [illegible]: [illegible] were [illegible] orchards [illegible] in May of this year (1982) [illegible]. These data will [illegible] (1982) and will be [illegible]. The [illegible] constraints [illegible] with [illegible] later this [illegible] to complete the data analysis and plan further testing of the GSS.

- Proposed three studies:

  1. Mini-lidar feasibility to monitor spray behavior above canopies.

  2. Mini-sodar to monitor upper air during field studies.

  3. Canopy characterization of forests for FSCBG input (See Witcosky).

- Need model evaluation protocol. EPA has these and Harold Thistle will pursue.

- Does not believe Kromekote cards in canopy can be used for spray accountancy as collection efficiency is function of wind velocity across the card and it is not practical to make this measurement. Cards work fine on ground. Teflon sphere used in canopy and washed off to get accountancy - error about 8% - interference due to wires (or whatever you hang the spheres with). (How does air velocity influence collection efficiency and how does one measure collection efficiency at each sphere?) Droplet sizes need to be above 30-40 microns. Work well to catch 30-300 micron drops. Spheres (ping-pong balls) were used in 1992 Utah canopy studies by Bruce Grim, et al.

- See Dave's letter and other papers in Appendix.

Pat Skyler

- FSCBG/AGDISP Model Technology Newsletter No. 3 will be released July 1992.

- Made about 70 FSCBG model runs this year for clients and to support field research.

Bill Steinke

- Conducted field tests for past four years on drift from ground sprayers treating dormant almond orchard.

- Conducted field test on drift of permethrin spray (12 um VMD) in fog in populated canyons.

- Mentioned ASAE standards for samplers and tracers - being reviewed.

- Has drafted a report for Jack Barry's review on field evaluation of Kromekote deposit cards.

- Mentioned that he and Al Womac would keep Jack Barry posted on agricultural committees involved with aerial and ground pesticide application.

Milt Teske

- Stressed importance of small drop (<33 um) accountability in model and drift studies. Wind tunnel data of droplet spectrum is for drops >33 um. Need to parameterize droplet spectrums and include small drops.

- Responding to Milt, Jack Barry mentioned that the FS has some wind tunnel quantitative data on small droplets and on a number basis the majority of droplets are <33 um. Jack will send this to Milt.

- Milt gave a presentation on status of FSCBG and AGDISP models and discussed the sensitivity study involving 400 separate FSCBG runs.

- Need to take another look at aircraft vortex decay.

- Milt's briefing is enclosed in the Appendix.

Harold Thistle

- Interested in statistical analyses of field data for model comparisons as is EPA.

- Need good upper air data during field testing for data interpretation and model inputs.

- Has access to bibliographies and data sets on meteorological studies in urban environments for those who have an interest.

- Agreed to obtain model testing protocol from EPA and provide to Jack Barry.

Dave Valcore

- Spray Drift Task Force (SDTF) is evaluating predicting drop size from physical properties of tank mix. (Bill Steinke and Milt Teske are also doing similar work).

- SDTF is comparing 1991 field data to FSCBG and DESDM model predictions. More field trials are planned.

- SDTF is actively pursuing model acceptance by EPA (OPP). (See sub-committee report.)

- SDTF is contracting Continuum Dynamics, Inc. to develop a model for air blast and ground hydraulic sprayers. Drift from air blast sprayers is now second highest priority of SDTF. UK has some type of ground spray model.

- SDTF has done a lot of work with dyes - most dyes are instable in sunlight. In drift studies this year they will be using photo stable tracers. Their work will not be published but data might be available via Dave Valcore.

- SDTF asked EPA and chemical companies to update pesticide application training and labelling - needs coordination.

- Need atomization data on air blast sprayers. (Suggest SDTF sponsor field tests using light scattering or other probes in the field to measure drop spectra).

Al Womac

- Conducted a drift study of turbine-powered (Thrush) aircraft, study results enclosed in Appendix. Two-thirds of agricultural aircraft sold today are turbine-powered. Noted more drift from slower speeds. Used high volume samplers and expressed concern that up to 95% of sample might be exiting on exhaust end.

B. Sub-Committee on Meteorology

Chairperson - Dave Whiteman

- Dave commented that charter of the meteorology sub-committee is too broad.

- Jack Barry responded that NSMAC would like for the sub-committee to develop guidelines and recommendations on type of measurements, measurement frequency, and measurement density for field studies involving model evaluations. It is recognized that guidelines would be tuned to scale of test.

[illegible] and more a lot of [illegible]

studies. In 1979 [illegible] this [illegible] they will [illegible] agree to do

possible reviews. Their work [illegible] not be published but data might

be available via Dave Williams.

Still need FAA and chemical company's to update pesticide

spray drift monitoring and labeling - needs more work needed.

Need dissemination data on air blast sprayers. [illegible]

[illegible]. Field tests using light scattering or other probes in the

field to measure drop size [illegible].

[illegible]

Conducted a brief study of turbine-powered (Thrush) aircraft.

Study resulted [illegible] in [illegible]. Two-thirds of agricultural

aircraft sold 1 day are turbine-powered. Noted more drift from

higher speeds. Used high volume samplers and expressed concern

that up to 30% of spray [illegible] on exhaust end.

[illegible] results on Meteorology

Discussion - Dave [illegible]

[illegible]

- Committee will also be asked to develop an outline for a "Rules of Thumb" manual for spraying in complex and/or forest terrain.

- Suggest that Dave Miller and Harold Thistle join the sub-committee.

- The status of minisodars, Global Positioning Systems, and weather station radio communication links was briefly reviewed for applicability to the aerial spraying problem. Recent research on the coupling and decoupling of valley and synoptic wind systems was summarized to suggest how this might prove useful in planning an conducting aerial spraying operations.

C. **Sub-Committee on Models in the Regulatory Process**

- Sub-committee met in Salt Lake City, October 1991. Dave Esterly was elected chairman. Attending were Milt Teske, Jim Bowers, Jim Rafferty, and Bruce Grim (DPG); Jack Barry (FS); and Dave Esterly, Dave Valcore, and Roger Drewes (SDTF).

- SDTF followed up in meeting Nov. 91 with EPA OPP - requested OPP EFGRG to pursue steps toward a model policy.

- Early '92 - positive response by EPA upper management and OPPE.

- EPA invited SDTF to meet with AREAL in Research Triangle Park - March 92. AREAL has model acceptance criteria.

- Agreement to have AREAL act as a scientific review board for model acceptance.

. . . will also be used to develop an outline for a "Guides of Audit" manual for surveying in complex and/or large terrain.

Support from Dave Whiting and Harold Thir [illegible] the [illegible] process.

The status of simulators, Global Point [illegible], and [illegible] [illegible] [illegible] [illegible] briefly reviewed for [illegible] [illegible] [illegible] [illegible]. General discussion on the [illegible] and [illegible] of [illegible] [illegible] [illegible] [illegible] [illegible] and [illegible] [illegible] in planning or conducting [illegible] [illegible] [illegible].

C. Subcommittee on Models in the Regulatory Process

Subcommittee met in Salt Lake City, October 1981. [illegible] was [illegible] chairman. Attending were [illegible] [illegible] [illegible], Jim [illegible], and Bruce [illegible] ([illegible]); [illegible] ([illegible]); and [illegible], Dave Vallero, and [illegible] ([illegible]).

EPA followed up on meeting Nov. 9, with [illegible] [illegible] - [illegible] [illegible] to [illegible] [illegible] [illegible] [illegible] [illegible]

Early '82 - [illegible] [illegible] response to EPA [illegible] memoranda [illegible] [illegible].

EPA invited SUB to meet with AMWA in [illegible] [illegible] [illegible] March '82. AMWA [illegible] model acceptance criteria.

• Agreement to have AMWA [illegible] a [illegible] identifying [illegible] model [illegible]

- SDTF annual meeting with D. Campt. Requested policy be formalized and developed, and acceptance criteria plans be jointly pursued - April '92.

- Positive response and plans for key contacts meeting the week of July 27, 1992 and formal meeting end of August 1992.

- SDTF welcomes others viewpoints.

III. RECOMMENDATIONS

A. Continue cooperative field testing and evaluation of FSCBG to understand reported under and over predictions of deposition and air concentration as function of downwind distance, and to build upon the confidence data-base; and encourage use of promising technology to support field testing.

B. Evaluate the significance of drops <33 um to deposition and drift predictions of FSCBG using existing data bases and recommends field testing if needed to fill data needs.

C. Develop a code for FSCBG to predict deposition impaction on target foliage and drift from air blast sprayers and other ground sprayers.

D. Enhance FSCBG for total accountancy of pesticide sprays and interface with environmental fate and impact models.

E. Support activities of this committee, user group, and SDTF in promoting acceptance of FSCBG by the scientific community and regulatory agencies, and international cooperators of spray models.

F. Accelerate development of atomization model that uses existing data-bases, physical properties, and constants to predict atomization.

G. Evaluate the revised VALMET model connect with FSCBG and AGDISP with existing or new field data sets.

H. Evaluate samplers for use in quantitating spray deposition and drift. The three types of samplers of primary interest are impaction (flux), deposition, and air concentration (dosage). Collection efficiencies are needed for the samplers along with comparisons to similar samplers.

I. Improve deposit/witness card spread factor technology and develop method of determining spread factors in the field. This is needed by those who want drop size and spray volume/mass data for model evaluation and calibration.

J. Develop recommendations for monitoring atmospheric processes when conducting tests to evaluate spray models. (A sub-committee chaired by Dave Whiteman was reaffirmed).

K. Enhance FSCBG for aerial application in urban and suburban areas. The USAF sprays for mosquitos in these areas, and the FS and APHIS treats gypsy moth in suburban areas.

L. Continue cooperation with Continuum Dynamics and FSCBG/AGDISP user groups on reviewing drafts of journal manuscripts for consistency of presentation and appropriateness of AGDISP and FSCBG model operations.

IV. SUMMARY

Third meeting of the **National Spray Model Advisory Committee** was held at Charlotte, NC, on June 23, 1992. The committee reviewed and updated recommendations from the 1991 Atlanta meeting, and reported on field testing and projects over the past year. The committee noted the support of management in encouraging and funding projects through technology development and other sources; and the progress that has been made in advancing the models since this committee was established. The participation and other support of our colleagues in industries, academia, and other agencies are recognized and appreciated, for without their involvement the utility of this committee would be minimal at best. My personal thanks to each of you in helping to develop, enhance, and transfer this technology. Our next meeting will be held at Spokane, Washington on June 24, 1993 the day following the 1992 International Summer Meeting of the American Society of Agricultural Engineers. Please mark your calendar as we are looking forward to seeing you there.

The [illegible] Field Advisory Committee was held at [illegible] on June 23, 1992. The minutes were reviewed and updated [illegible] from the 1991 Atlanta meeting and reported on field testing and projects over the past year. The committee noted the support of management in encouraging and funding projects through technology [illegible] and the progress that has been made in [illegible] the models since this committee was established. The [illegible] and active support of our colleagues in industry, [illegible], and other agencies are recognized and appreciated. The ultimate [illegible] the utility of this committee would be stated at best, in personal thanks to each of you in helping to develop, evaluate, and transfer this technology. Our next meeting will be held at Spokane, Washington on June 21, 1993 the day following the 1992 International Summer Meeting of the American Society of Agricultural Engineers. Please mark your calendar as we are looking forward to seeing you there.

APPENDICES

A. Attendees and Addresses

B. Committee Membership and Addresses

C. Committee Member Reports

D. Professional Papers

Appendix A

Attendees and Addresses

ATTENDEES

NATIONAL SPRAY MOEDL

ADVISORY COMMITTEE MEETING

CHARLOTTE, NC

June 23, 1992

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Appendix B

Committee Membership and Addresses

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Appendix C

Committee Member Reports

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To: National Spray Model Advisory Committee

Fm: D. R. Miller

Date: 20 June 1992

We in the North East Aerial Spray Technology Group have discussed the need to develop several pieces of technology for use in spray operations, spray trials and field experiments where FSCBG or similar models are used or tested. We think that the three listed below are of high priority and appreciate hearing the reactions of this committee to them.

1. The use of a **mini-lidar**, available from the Los Alamos National Lab, in a spray drift study this summer by the NEFAAT group to study the movement of spray material above a hardwood forest.

We would like to arrange for the Los Alamos lidar, with their personnel to run it, to take part in our drift study in Aug-Sept 92 as a pilot project to see if it will work and what its limits/resolutions/etc. are. If it works as we think it will, we will then make proposals to acquire or use one for future studies. Approximate cost is $25,000 this summer. An outline of its use in our project this summer is attached.

2. The construction of a **mini-sodar** (acoustic radar) for onsite measurement of wind speed and direction profiles above the forest canopy for input to the FSCBG model and use in spray operations.

The wind speed and direction above the canopy are a critical environmental control of spray movement. The current operational technology for measuring these (primarily teathersondes and extrapolation from ground stations) are difficult and extremely inaccurate. The mini-sodar described in the attached material (Coulter and Martin, 1992) may solve this problem. It is easily transported, operable from the ground by one person and is reported to give accurate, real-time, measurement of wind profiles just above forest canopies. We have talked Dr. Coulter at Argonne National Lab and he will supervise the construction of one for us. Approximate cost $25000 over the next year.

3. A project to measure and **catalog canopy LAI profile shapes** from each of the major timber types in the US, for use in FSCBG and other models.

Realistic calculations of deposition in canopies and on the ground below canopies requires input of leaf area density at the various levels in the canopy. The LAI-2000 sensor makes routine measurement of the canopy total LAI easy. But distribution of this total over the whole depth of the canopy is very difficult. If a file containing the shape of the canopy density profile (the proportion of leaf area at each level in the canopy) for each timber type was available in FSCBG then a routine measurement from the ground is all that would be needed as input to the model. The attached paper (Wang et al. 1992, Forest Science (in press)) and documentation describes how these profiles can be measured. Approximate cost $200,000 over three years.

PROPOSAL

CHARACTERIZATION OF LEAF AREA PROFILES IN THE MAJOR EASTERN HARDWOOD FOREST TYPES

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BACKGROUND

The geometry of forest canopies is a major determinent of the dispersion and deposition of spray materials, biological and chemical, that are applied to forest canopies to control insect pests such as the Gypsy Moth (Lymatria dispar). Not only does the canopy architecture determine the arrangement and relative efficiency of catchment surfaces, but it also effects the air movement and turbulence which transport the aerosols (Miller et al., 1992; Wang et al., 1990; and others).

In the last decade, research models have been used to investigate the physical environment of these insects in the canopy (Anderson and Miller, 1988) and the movement of air and particles in canopies (Gao et al. 1989; Li et al. 1990; Miller et al, 1991; Baldocci et al. 1989; and others). Planning and operational tools, such as the FSCBG numerical model have become available to help the forest pest manager. Application of this new understanding requires detailed information on the arrangement of the foliage in the forests. Thus progress in the transfer of much of the new research results to operational tools and the extensive adaptation and use of tools, such as FSCBG, depends on the availability of canopy measurements.

The size and variability of forest canopies makes widespread hand sampling of leaf area distributions out of the question. But all of these models and many ecological models require imputs of vertical profiles of leaf area density, or some similiar measurement. There has been an extensive amount of research on the use of light penitration of canopies to remotely estimate their leaf areas (Anderson, 1971; Bonhomme and Chartier, 1972; Wang and Miller, 1987; and others). The most sophisticated of these studies utilized hemispherical or "fisheye" photographs for the field measurements. In 1989, an electronic light sensor was marketed (Welles and Norman, 1991) which eases the measurement and reduces

the data reduction tasks by an order of magnitude. We have tested this sensor and combined it with our auto-positioning system (Wang et al., 1992), which allows us to measure the leaf area profiles in any forest stand more easily and accurately than before.

We propose here that typical leaf area profiles of each of the extensive forest types in the Eastern Deciduous Forest be measured. Since the branching and leafing habits of each tree species are consistant from site to site (Horn, 1970; Wang and Miller, 1987), these typical profiles can be used whenever operations are conducted in stands with species mixes similiar to those measured. The accumulated library of typical leaf area profiles can be made available as look-up tables in models or deciminated electronically, i. e. on a floppy disk, to other users of spray materials.

OBJECTIVE

To measure leaf area density profiles in "typical" forest stands in each of the twenty major hardwood forest types in the Eastern U.S. and condense them into an electronic library for use by spray operation planners.

PROCEDURES

1. Select stands with known composition and stocking for measurement from long term management, research and inventory plots throughout the eastern U.S. Preferrably, several stands with different stocking levels in each type will be found. Approximately 40 different stands will need to be sampled.

2. In each sample stand five profiles will be measured and averaged using a movable telescoping tower, self-leveling platform and the LSI-2000 sensor as described in Wang et al.,1992). Also, a cruise will be conducted in each stand which does not have a recent inventory available.

3. Tables of Leaf Area Density profiles as a function of species composition and stocking will be produced from the measurements.

PROJECT MANAGEMENT

The principle investigators at the University of Connecticut (UCONN) will train a crew of three field workers (preferrably USDA employees) in the field procedures and use of the equipment and sensors. USDA FPM cooperators and the UCONN investigators will jointly select the stands to be measured from available information. The USDA FPM cooperators will arrange access to the sample stands. The crew of three will then travel to each stand and conduct the field measurements. The data will be returned to the University of Connecticut for quality control, summerization and incorporation into the product tables.

```
                             SCHEDUAL
                                 1993         1994
Task                          JFMAMJJASOND JFMAMJJASOND

Accumulate Instruments        ---

Train Crew                     ---

Select Sample Stands          -----

Sample Stand Measurement         --------

Data reduction and analysis             ---------

Report preparation                              ------
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APPROXIMATE BUDGET

	UCONN (data and training)	USDA (field measurements)
PERSONNEL		
Salaries:		
Research Asso. 50% for 1 year	20000	
Technician 15% for 1 year	5000	
Graduate Student 50% for 2 years	30000	
Field crew 3 for 1 year		75000
Benifits:		
@.4 of salaries	20000	30000
EQUIPMENT		
LSI 2000 Sensors 2 at 6000 each	6000	6000
Hydraulic tower and pole		7000
Miscellaneous hardware		2000
SUPPLIES		
Computer and Lab	3000	
Field		5000
Repair parts	3000	5000
TRAVEL		
P.I.-Planning Conferences and Site Selection 6 trips @ 1000	6000	
Travel to measurement sites Per diem, 3 personnel @ 50/day for 100 days.		15000
Milage @ .5 for 10000 miles		5000
INDIRECT COSTS AT.48 OF DIRECT COSTS UCONN MATCH	(441600)	
TOTALS	92000	150000

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SPATIAL VARIABILITY OF CANOPY FOLIAGE IN AN OAK FOREST ESTIMATED WITH FISHEYE SENSORS

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J. M. Welles
G. M. Heisler

ABSTRACT

The vertical distribution of forest canopy elements is an important factor in canopy-atmosphere exchange processes and knowledge of the shape of the average vertical profile of leaf area density is a critical input to models of these processes. This study was conducted to determine the spatial variability of Leaf Area Index (LAI) in an Oak forest when estimated with indirect fisheye techniques. A 35mm camera with a 180° hemispherical lens and a LI-COR LAI-2000 Plant Canopy Analyzer (wavelengths < 490 nm) were used simultaneously to estimate vertical leaf area profiles and the horizontal variability in an oak forest in central Pennsylvania. Measurements were made at eight different heights in the canopy and repeated at 9 different locations. The two sensors were in reasonable agreement. The photographic technique estimated the total leaf area index (LAI) to be 3.58 and the light sensor estimates resulted in an estimate of 3.40. The average precision was 8% for the LAI-2000, and 17% for the photographic technique. The point to point spatial variability of the LAI estimates was low when the whole canopy was measured from the ground and quite high when measuring the upper canopy. Ground level estimates of LAI using these fisheye techniques spatially average the canopy to the

point where only 4 replications were necessary to sample the total LAI with 90% confidence.

ADDITIONAL KEY WORDS. Leaf Area Index, Leaf Area Density, Plant Canopy Analyzer.

INTRODUCTION

Canopy element distributions have not usually been measured in forest inventories in the past. But the importance of canopy architecture to radiation regime within plant canopy and to the gas and energy exchanges in a stand has been well established in the literature (i.e. Ross, 1981; Gates, 1980). This critical role of canopy structure is sure to make it a characteristic that is sensitive to changes in environmental stress on the stand (Waring, 1985). The ongoing issues of forest decline and long term health are providing incentive to include measurements of canopy density in routine forest monitoring and inventory operations.

The relationship between plant canopy structure and radiation regimes within the canopies have been studied for several decades. Extensive reviews of this topic can be found in several books and a number of articles such as Ross (1981), Anderson (1971), Norman and Campbell (1989), and Campbell and Norman (1989). Since the beam solar radiation penetrating a canopy is directly related to the canopy gap fraction, it can be used as a natural probe to detect the plant canopy structure. The basic approach of this method is to establish a light penetration model for a canopy with specific foliage distribution assumptions, the light penetration model then can be inverted to compute the leaf area index. With an assumption of random foliage distribution in the canopy space, Monsi and Saeki (1953) constructed a Poisson beam penetration model.

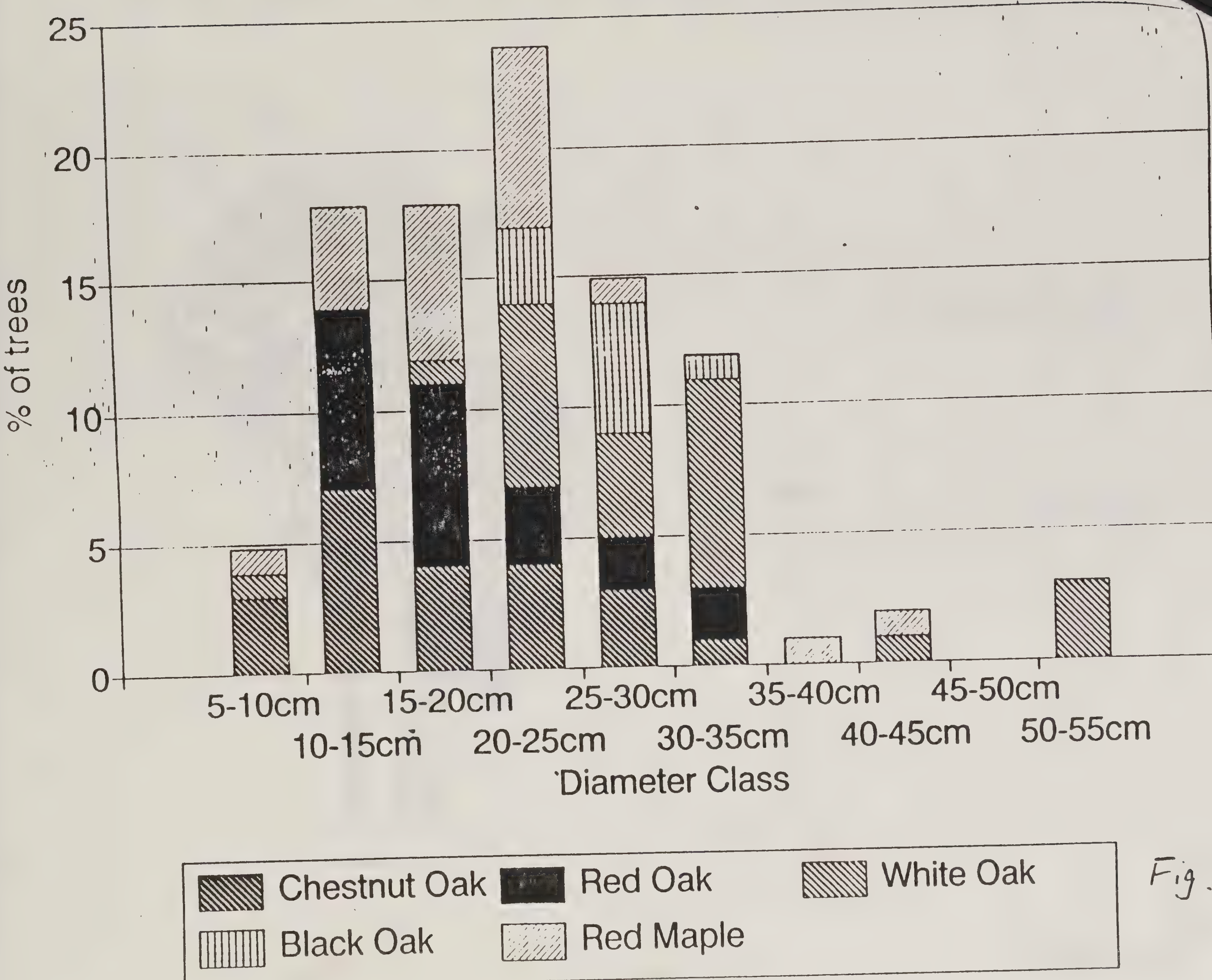
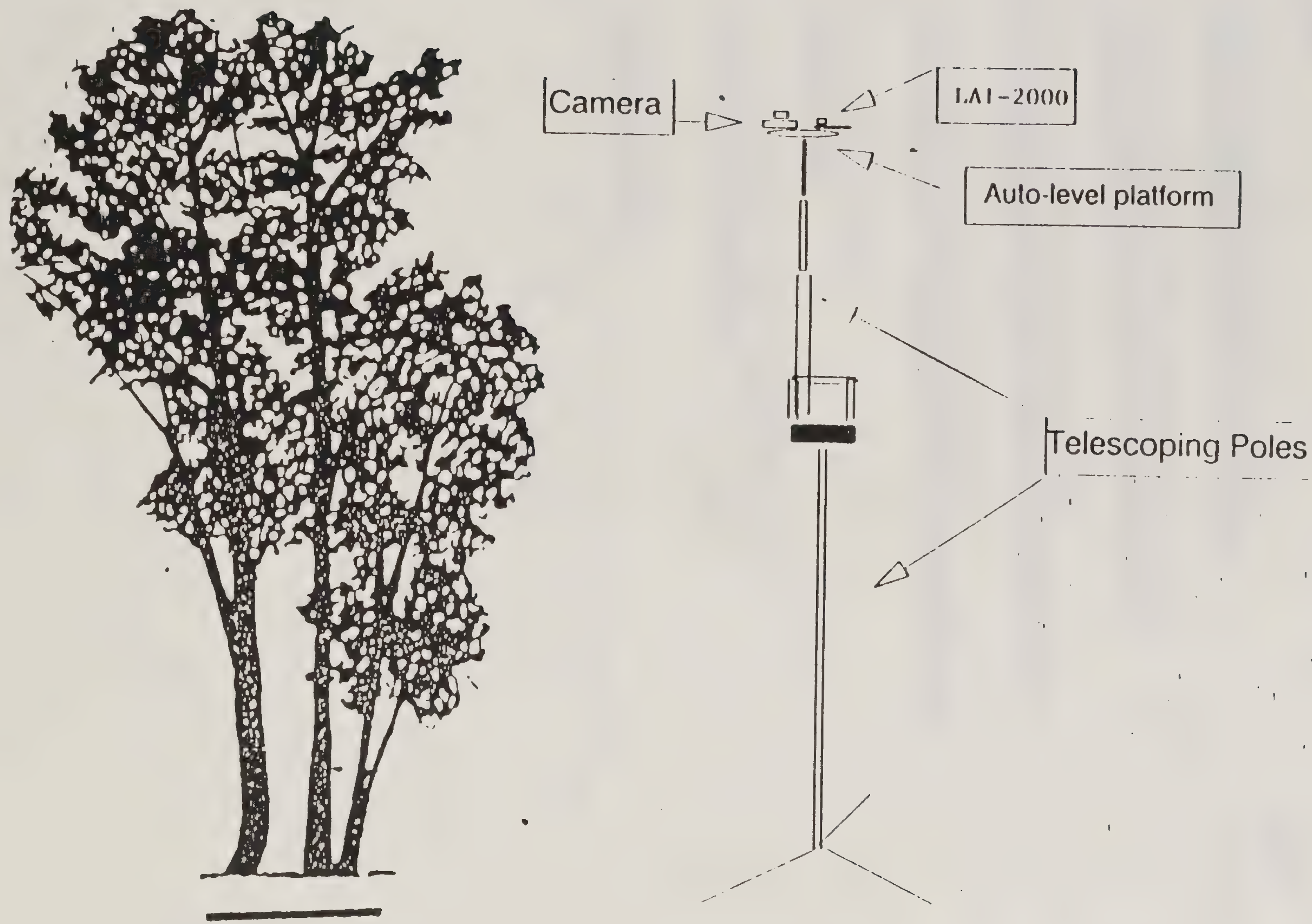
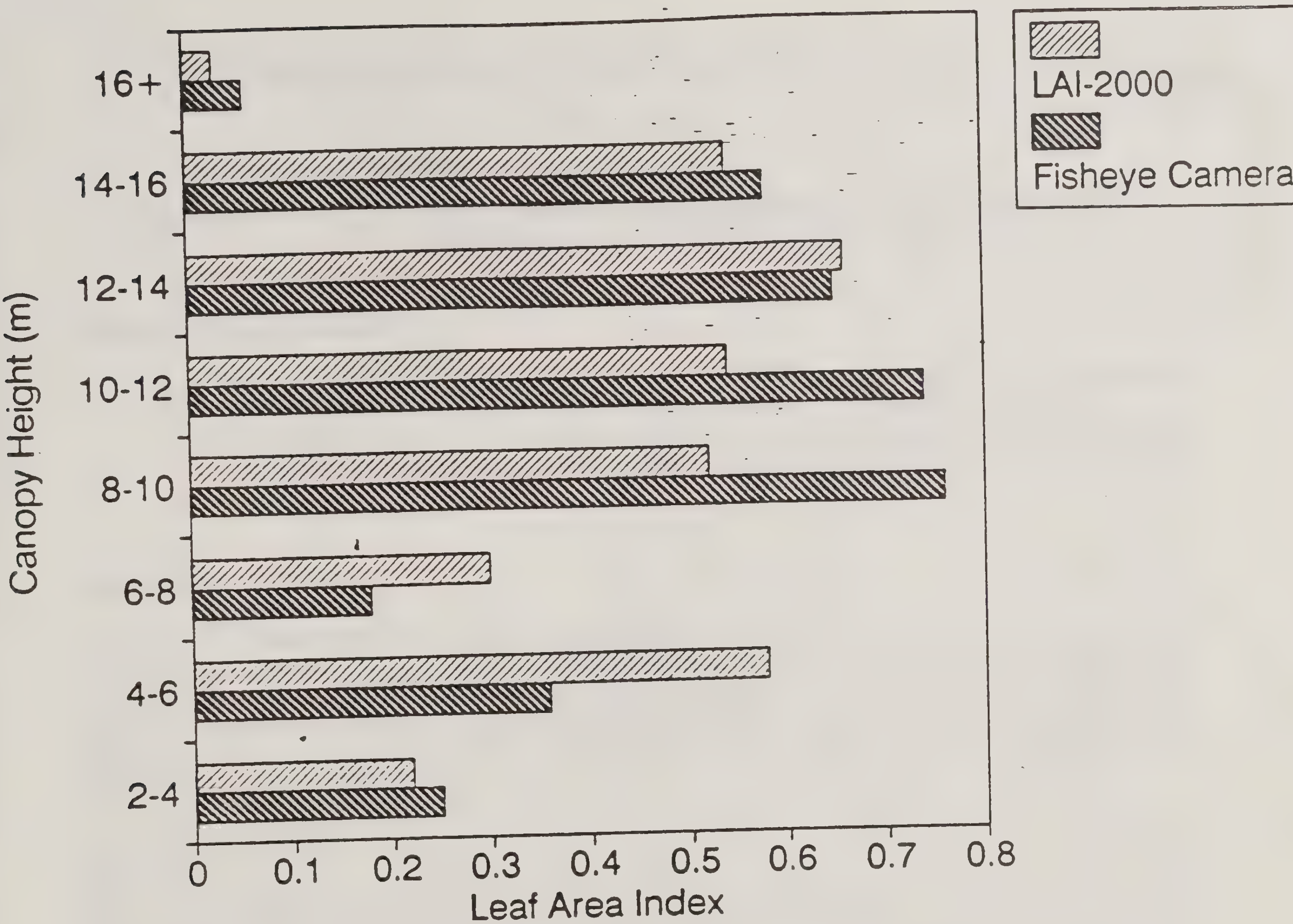

25
20
15
10
5
0
% of trees
5-10cm
10-15cm
15-20cm
20-25cm
25-30cm
30-35cm
35-40cm
40-45cm
45-50cm
50-55cm
Diameter Class
Chestnut Oak
Red Oak
White Oak
Black Oak
Red Maple

Fig. 1



Camera
LAI-2000
Auto-level platform
Telescoping Poles



LAI-2000
Fisheye Camera
Canopy Height (m)
16+
14-16
12-14
10-12
8-10
6-8
4-6
2-4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Leaf Area Index

Fig. 3

PROGRESS REPORT ON WORK WITH THE FSCBG MODEL

May, 1992

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Project Objectives:

1. To verify the usability of the model in hardwood forests.
2. To develop criteria for using it in hardwood forests.
3. To determine if enhancements, or changes in the model would be helpful in gypsy moth control operations in hardwood forests.

Progress:

Field experiments were conducted in 1988 and 1990 in a tall hardwood forest in central Pennsylvania to provide measurement data to verify the FSCBG model (Objective 1). Spray runs were made under a wide variety of meteorological conditions and two different leaf sizes (leaves fully expanded and leaves half expanded). Detailed descriptions of the forest and experiments are given in Anderson et al. (1992).

Our examination of the FSCBG model began in 1989 when a mainframe version of the FSCBG model was obtained from the U.S. Army meteorology unit at Dugway Proving Ground and installed on the IBM main frame at the University of Connecticut. We encountered considerable problems with this version and were working on debugging it when Continuum Dynamics was contracted to adapt a microcomputer version of FSCBG. At that time we suspended trying to work with the main frame version and in late 1990, received our first microcomputer version FSCBG(PC) from Continuum Dynamics. We used FSCBG(PC), versions 3..., to run the model for our experimental situations. Anderson et al. (1992) presents the computations of FSCBG(PC) 3.05 compared to our 1988 field experiment data.

We asked for and received a copy of the FSCBG(PC) version 3.05 code. We wanted to inspect the code for two reasons. First to assure ourselves that we knew what the model calculated and second to try to reconcile several serious calculation problems "bugs" which we could not solve in the mainframe version and were apparently still present in the PC version. We did spend considerable time examining the code and attempting to follow its logic, etc. I had several talks with Dr. Milt Teske about a number of problems we encountered with version 3.05. With his advice, we were able to work around these and run the model against our 1988 data.

Meanwhile Continuum Dynamics had contracted to "clean up" the FSCBG code and, FSCBG version 4, was made available in early 1992. We are currently running the FSCBG, version 4... to simulate our

1990 experimental data. The draft comparison paper (Miller et al. 1992) will be available shortly for review. Dr. Teske should be complemented on his work on this version; it is an order of magnitude improvement in the I-O portions of the model, and a number of calculation and coding errors have been corrected. At the time of this writing (May 1992) only one major "bug" remains in the FSCBG(PC) code that I am aware of. The model calculates a much higher deposition in the top meter of the canopy that it should. Milt has sent me a temporary version which skips around this problem to use while he works out the "bug".

Future Work:

We currently have a very good working arrangement with Dr. Milt Teske at Continuum Dynamics. His work with the code and response to our questions and problems has made it unnecessary and undesirable for us to try any modifications on our own.

We have made independent numerical calculations of a number of the processes modeled in FSCBG, such as the wing vortex entrainment process and the lagrangian transport of droplets and the evaporation processes (Wang, et al. 1991, 1992a, 1992b). These are being used with our field data to study the physics of the various processes in the hardwood forest and fill in gaps in our knowledge of how the micrometeorological turbulent air characteristics effect the transport and dispersion above and in the canopy. We currently have an evaporation experiment going on to measure the droplet evaporation rates in *turbulent* air after the droplets leave the vortices. We plan to develop formulas to help calculate the evaporation of the materials used in gypsy moth control.

As work is completed on objectives 2 and 3 above, we plan to suggest and discuss them with Dr. Teske, Dr. Barry and other responsible parties to see if it would be desirable for Milt to incorporate them into FSCBG. Our evaporation calculations and some of the "criteria" suggestions should be out in 1992.

In summary, we have only looked at the FSCBG code for our own education and have not made any attempts to change it. We have no intention of changing the code in the future. If we have suggestions for changes we will make them to Jack Berry and Milt Teske and they can decide if they wish to make any modifications.

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Use of a Small Minisodar to Measure Tributary Drainage Flow During ASCOT 88*

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INTRODUCTION

The contribution of tributary flow to the strength, amount, and dynamic of valley drainage flow is an important part of the Atmospheric Studies i COmplex Terrain (ASCOT) program. Studies in Brush Creek Valley, Colorado, i 1982 and 1984 (Orgill et al., 1985; Porch et al, 1989a; Coulter et al., 1989 Porch et al., 1989b) found complex interactions of the flow from a tributar with both the main valley flow and the mesoscale flow above the valle system. Within the tributary, flow oscillated with period near 15 min similar behaviour associated with an oscillation in the main valley flow ha been found in tributaries draining into a nearby valley (Porch et al. unpublished information 1990). Evidence from the Brush Creek study support the existence of a vertical circulation cell, oriented perpendicular to th main valley drainage and including the tributary, that can produce significan subsidence above the tributary and a seemingly inordinate contribution fro the tributary to the total drainage volume of the main valley, depending upo the mesoscale wind direction. Although these complexities of flow dynamic are usually not included in numerical model prediction schemes for pollutan dispersion because the scale of the interactions is less than the grid size this scale may be the most critical for dispersion in the immediat neighborhood of a chemical or power plant in complex terrain.

The ASCOT campaign in 1988 was designed to evaluate the relative drainag effectiveness of valleys with different shapes and orientations to th mesoscale wind direction. A part of this campaign was devoted to th investigation of the relative importance of different tributaries to a singl main valley drainage system. It was necessary to measure wind profiles in a many locations as possible. To facilitate this effort, a very small minisoda was developed and used. The techniques and instrument developed for thi purpose and some of the results are discussed in this paper.

INSTRUMENT DESCRIPTION

The antenna for the minisodar consists of a 4 X 4 array of piezocerami tweeters similar to those described by Coulter and Martin (1986). Tilte beams are produced by imposing a phase difference of 90 deg between adjacer diagonal rows in the array. Since seven such rows are in a 4 X 4 array, th total phase change across the array is 540 deg. Two tilted beams are produce by using orthogonal sets of diagonals. The third, vertical, beam is produce with all elements in phase. The antenna for the 4 X 4 array is about 0.5 m c a side. This is the smallest practical arrangement that maintains reasonabl

*Work supported by the U.S. Department of Energy, Assistant Secretary for Energy Research, Office of Health and Environmental Research, under contract W-31-109-ENG-38.

array (Coulter et al., 1988) produces more beam control and reliability but is less portable.

Additional reductions in system weight and portability were achieved by using thin (1.2-cm) plywood for t͘ɔ enclosure, limiting the enclosure height to 0.75 m, and using only a single sheet of corrugated foam for sound reduction. Such operation is made possible by the relative lack of noise sources at the operating frequency of 4500 Hz and by the relatively quiet locations in which the system was used.

Further size reductions were realized by eliminating the use of a reflector; i.e., the array faced upward in a horizontal plane. Thus it was not possible to operate during precipitation, which can be done when a reflector is used (Coulter and Martin, 1987). The weight of the antenna enclosure is approximately 12 kg, so that it is easily deployed by a single person. The computations are performed by a small computer with an operating system identical to that described by Coulter et al., (1988). Ample power was supplied by a 1-kW generator.

STUDY DESCRIPTION

The tributary drainage study, during July 1988, was centered around the main valley of Kimball Creek (KC) , Colorado, USA, oriented west to east and approximately 18 km west of its confluence with Roan Creek Valley. The two tributaries discussed here are separated by about 0.5 km and drain into KC from the south from 180 deg (TSE) and from 205 deg (TSW) (Table 1, Fig. 1). The general dimensions are similar to those of Pack Canyon, a tributary of Brush Creek studied in 1988 (Coulter et al., 1989). Figure 1 shows that TSW has sidewalls of approximately equal heights while TSE has higher sidewalls to the east (down KC) than to the west. TSW and TSE share a common sidewall that extends somewhat less into KC than do the sidewalls to the west of TSW and the east of TSE. Note also the protrusion into KC from the south about 1 km east (downstream) of TSE.

The minisodar data, consisting of 1-min averages of wind speed, wind speed variance, and signal amplitude, are the primary basis for the analysis

Table 1. Measurement times, locations, characteristics and conditions during July 1988. Distances are relative to KC-Tributary junction

Site	UTMX	UTMY	Date	Time (MST)	Ht. (m)	Distance (m)	Cloud Cover
TSE1	717.8	4370.6	25	2206-2359	12	156	Clear
TSE2	717.8	4370.3	26	0035-0200	25	469	"
TSE3	717.8	4370.2	26	0232-0336	28	614	"
TSW1	717.2	4370.6	22	2149-2252	12	132	Ptly cldy
			28	2056-2303	12	132	" "
TSW2	717.2	4370.3	22	2324-0026	36	422	" "
			28	0055-0210	36	422	Clear
TSW3	717.2	4370.1	23	0050-0210	49	578	Ptly cldy
			29	0055-0210	49	578	Clear

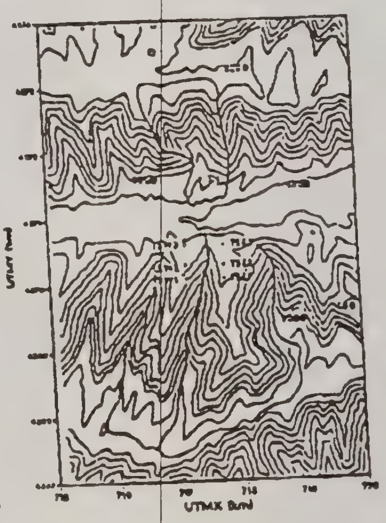

Fig. 1. Topography of the site including instrument locations. The drainage areas are outlined in thick lines.

simultaneous profile measurements in TSW and TSE to verify this tentative conclusion.

This study has shown that seemingly small differences in topography within and near tributaries can have meaningful effects upon the transport and dispersion within nocturnal drainage flows, in part because the flows within the tributaries are so light that they are responsive to small external influences. Only a few of the possible variations were observed (no counter tributary mesoscale flow was encountered, for example).

This study has also shown the utility of a portable sodar in rugged terrain accessible only by four-wheel drive vehicles, or only on foot. Such a system could become truly miniaturized through use of data transmission with radio and with battery operation, both of which should be possible.

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Brian Prendergast
William Yendol

Progress Report

Administrative Summary

A Study to Determine Dimilin Residues and Persistence on a Northeastern Oak Forest After Aerial Application

A Cooperative Effort By the
Northeast Forest Aerial Application
Technology Group (NEFAAT)

Brian F. Prendergast and William G. Yendol

The Pennsylvania State University
Department of Entomology
Aerial Application Technology Laboratory
University Park, PA 16802

A fifty acre, oak forest block in central Pennsylvania was sprayed by air with Dimilin 25W at the label-specified rate of 0.5 oz per acre. Leaf samples were collected from the upper and lower canopy, and the understory, of 27 oak trees within this plot on the day of spray, May 29, 1991, and on May 31, June 10, July 29 and September 26, 1991. Litter samples were collected on October 31 and November 14, 1991. Soil samples were also collected on each of these seven days. Samples are presently being analyzed to determine Dimilin deposit and persistence on these strata. A high pressure liquid chromatographic system is being used for the analysis.

The FSCBG model using the multiple swath deposit prediction portion is also being compared with the actual Dimilin deposits on artificial targets above the canopy and at ground level. Spherical targets were suspended from wires between 60 ft towers that ran perpendicular to the flight line. Extensive weather data was collected and used as input for making model predictions. Leaf deposit data will also be compared to FSCBG predictions.

An analytical technique for measuring Dimilin residues on leaf surfaces and artificial targets was developed as part of these investigations. This method has been found to be less expensive and as accurate as previously established methods; ethanol is used in lieu of more costly and more toxic solvents and cleanup is performed using solid phase extraction cartridges which further reduces solvent use. Measurements are made using HPLC.

Dimilin residues on canopy leaves collected immediately after spray (May 29, 1991) averaged 50.51 ng/cm^2 per tree on 23 trees. Dimilin residues on canopy leaves collected 2 days post-spray (May 31) averaged 13.21 ng/cm^2 per tree on 21 trees processed to date. Dimilin residues on canopy leaves collected 12 days post-spray (June 10) averaged 13.04 ng/cm^2 per tree on 18 trees processed to date. Dimilin residues on leaves collected 62 and 90 days post-spray are still being measured. The decrease in Dimilin residues between the day of spray and two days post-spray was

probably due to a severe thunderstorm which occurred on the day of spray. Our persistence data is consistent with results from similar studies of Dimilin persistence in forest ecosystems.

The deposit of Dimilin at ground level averaged 0.026 ug/cm^2. The deposit above the canopy is presently being analyzed. The full progress report is available on request.

Milt Teske

USDA Forest Service Aerial Spray Models AGDISP and FSCBG

1992 Model Status Report

Milton E. Teske
Continuum Dynamics, Inc.

National Spray Model Advisory Committee
Charlotte, North Carolina
June 23, 1992

Summary

Status of the Models: Training Sessions, Latest Versions

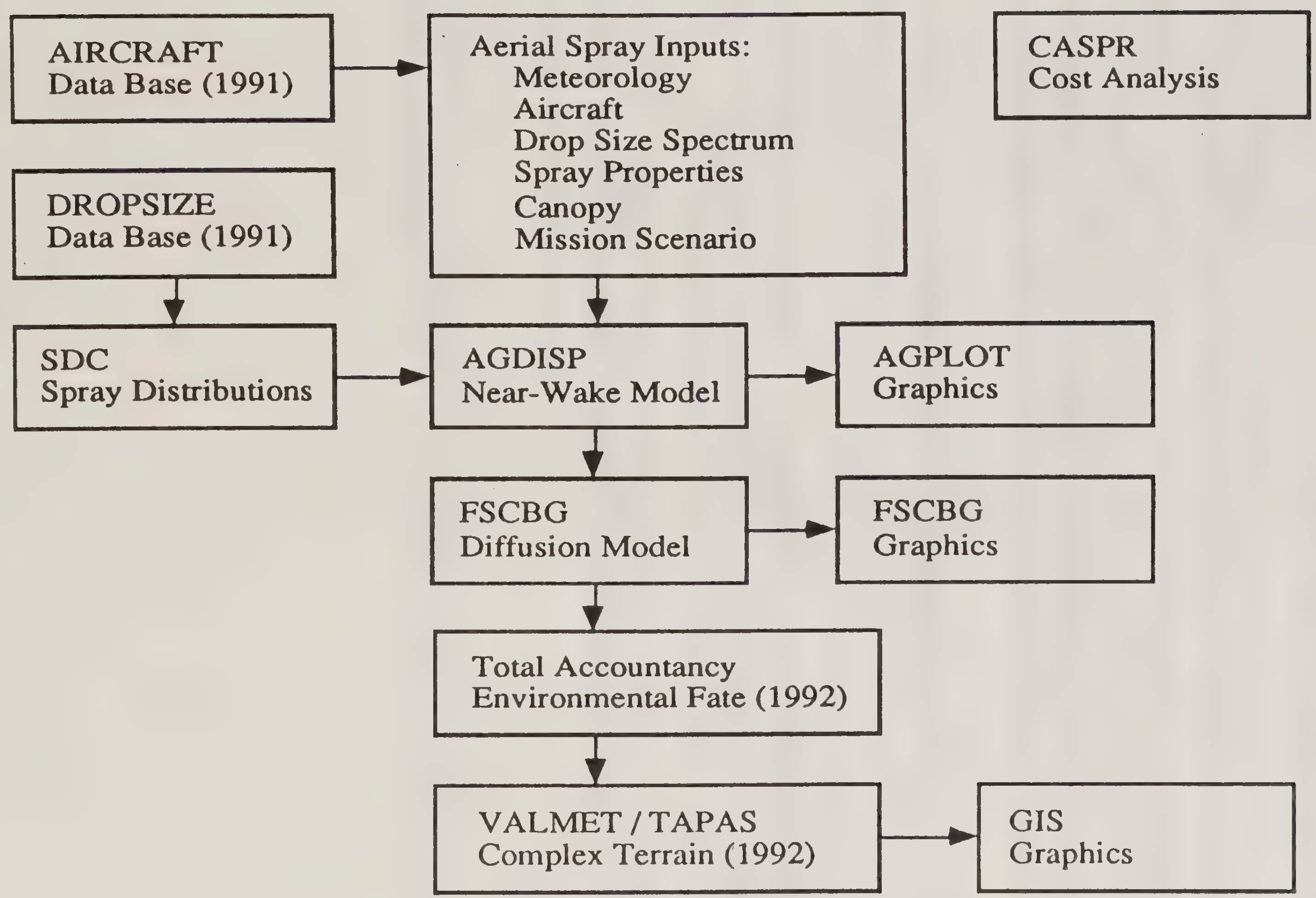
Publications

New Features to be Included

Unsolved Mysteries

Other Topics

The Whole Enchilada



Status of the Models

FSCBG

4.0 came together in Fall 1991

Las Cruces gummy bear training session (November 5-8)

Formal 4.0 release January 15, 1992 with the features (as discussed in ASAE preprint 921069: "FSCBG 4.0 Aerial Spray Model" by Curbishley, Skyler, Teske and Barry):

- New interface makes operation easier
- Default data and libraries
- Mixed units on all variables
- Input checker
- Extensive graphical capability
- Modular construction for future expansion

Princeton training session (March 16-19, 1992)

AGDISP

User Body Count: 39 AGDISP; 56 FSCBG; 1 newsletter

Publications

"ABCs of FSCBG" -- a nontechnical overview of the model

"One-On-One Manual" -- a self-help guide

"User Manual" -- a discussion of all the program features

"Technical Manual" -- a compendium of the equations (also to appear in *Environmental Toxicology and Chemistry*)

FSCBG technical overview -- in preparation for *Transactions of the ASAE*

Note on Net Radiation Index -- tying solar location to the evaluation of this input parameter

Summary of the anemometer tower experiments that lead to the evaluation of the Vortex Decay Coefficient -- in preparation for *AIAA Journal*

Complete Model Input Sensitivity Study -- reported in ASAE preprint 921086

Input Sensitivity

Over 400 FSCBG runs were carried out to establish the sensitivity of all inputs to the aerial application problem as defined by the model. The overall sensitivity factors, as described in the paper, include the consistency in swath deposition shape and the drift pattern downwind for both helicopter and fixed-wing aircraft with rotary and flat fan nozzles. The percentage factors generated by the analysis (the top ones at least) become:

VARIABLE	DEPOSITION	DRIFT
Wing Span	3.185	1.033
Release Height	1.981	1.892
Specific Gravity	2.125	0.805
Nozzles Horizontal	2.429	0.371
Rotor Diameter	1.456	0.961
Wind Speed	1.166	0.981
VMD	0.771	1.154
Atmospheric Pressure	1.492	0.412
Spraying Speed	1.504	0.388
Canopy Height	1.562	0.152
Wind Direction	0.750	0.765

New FSCBG Features

Anticipate release of FSCBG 4.1 in Oct/Nov 1992. Some of its new features will include:

- Swath Width Evaluation
- Enhanced Screen Graphics
- Library Extension and User Access
- On-Line Help Facility
- Data Export
- Run Time / Disk Space Estimation
- Discrete Receptors Enhancement
- Total Accountancy Computation
- Root/Normal Drop Size Specification
- Nonparallel Flight Lines
- DOS / User Utilities

DC-3 Swath Width Study

AGDISP was used in the last year to evaluate the swath width of the DC-3 (Twardus and Ghent). The APHIS guideline for the DC-3 is:

300 feet

AGDISP calculations several years ago suggested that the swath width should really be considered:

201 feet (COV = 0.3)

A field test last fall concluded that the swath width (flying inwind) is between 137 feet and 291 feet (given the limited amount of field data collected and assuming a 90 percent confidence interval) with an average value of:

214 feet

Drop Sizes by Normal Probability

An approach to collapsing the drop size distribution data base compiled by Skyler and Barry (from all available USDA Forest Service wind tunnel studies) was followed and reported on at the recent ILASS conference in San Ramon, CA.

Here, the technique by Simmons (1977) and Tate and Marshall (1953!) plots the Cumulative Volume Fraction on a normal probability distribution scale as a function of the square root of the drop diameter. The results were generally so startling when first discovered that the authors felt compelled to dismiss divine intervention and intimate that the correlation was purely empirical and should not be used as a basis for theoretical interpretation.

This becomes a "root/normal" approach when normalizing by VMD and optimizing the common area under the Volume Fraction curve. A two-parameter set (VMD and slope) replaces the drop size distribution.

This work will be extended to include the neural network techniques at Dupont, and published in *Atomization and Sprays*.

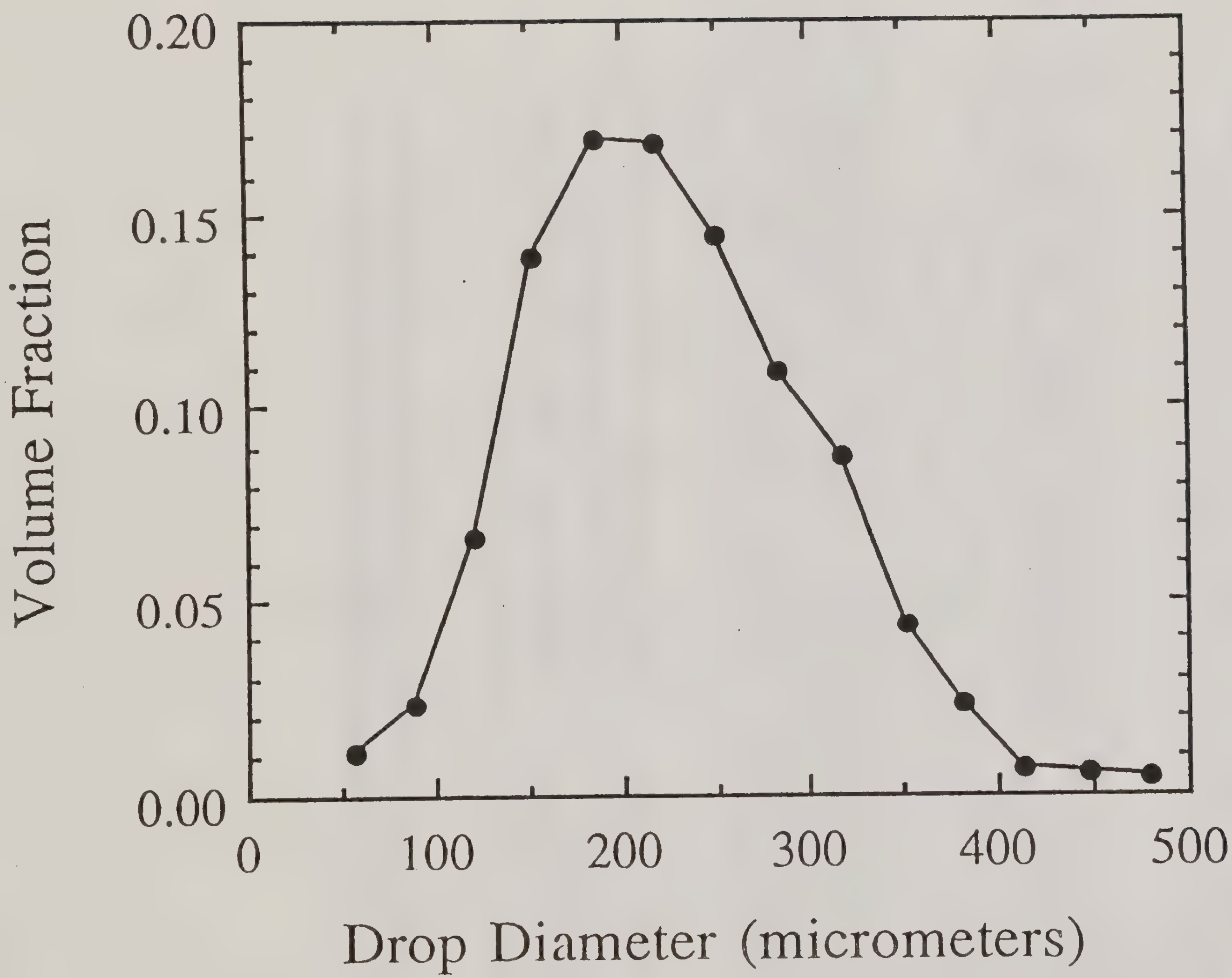


Figure 1. Spray drop size distribution volume fraction for an 8001 flat fan nozzle, spraying water and oriented zero degrees (parallel) to a 50 mph air stream. Pertinent drop diameters are $D_{0.1}$ = 121.39 µm ; NMD = 75.30 µm ; SMD = 178.46 µm ; VMD = 204.77 µm ; and $D_{0.9}$ = 310.56 µm.

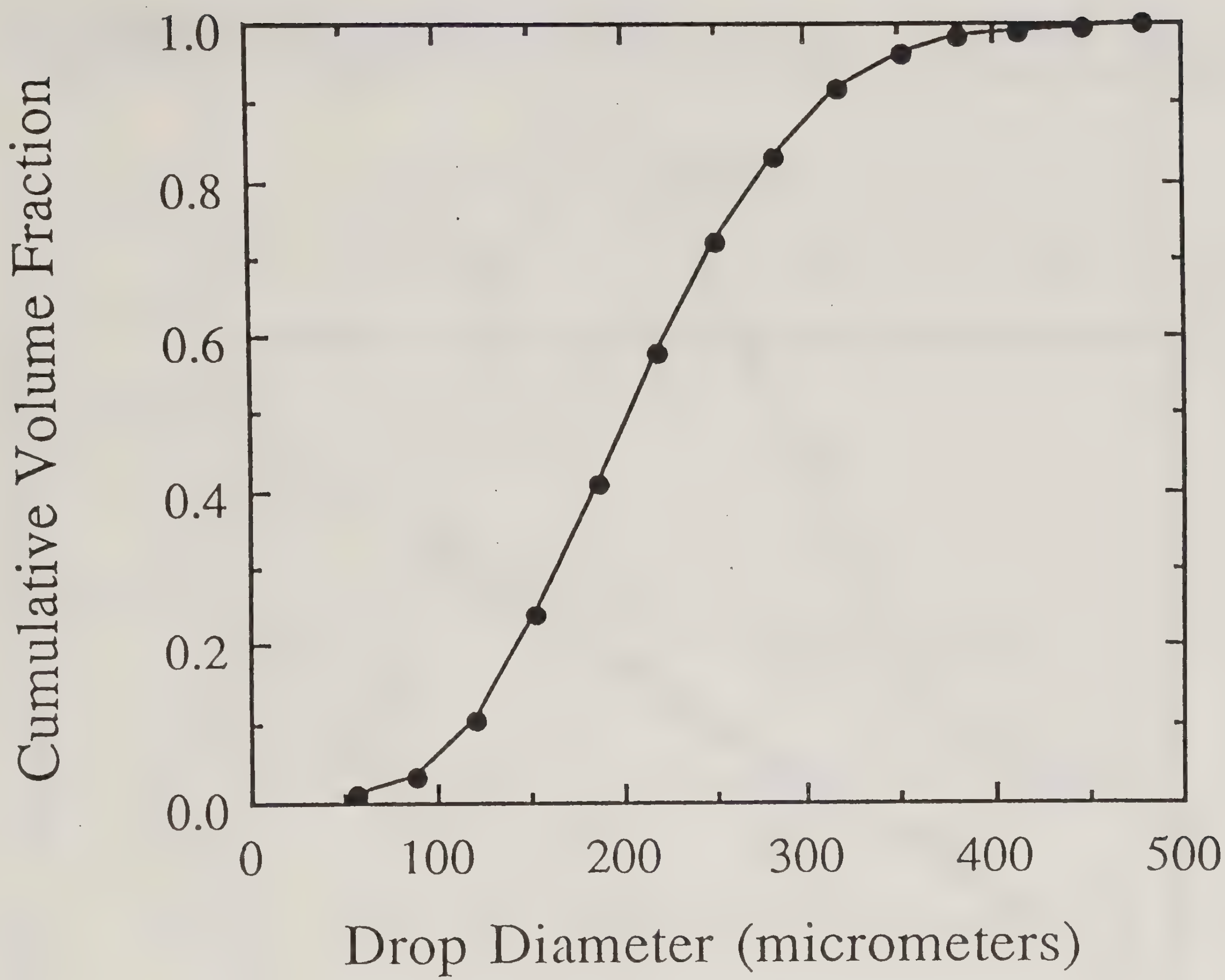


Figure 2. Cumulative volume fraction for the drop size distribution given in Figure 1.

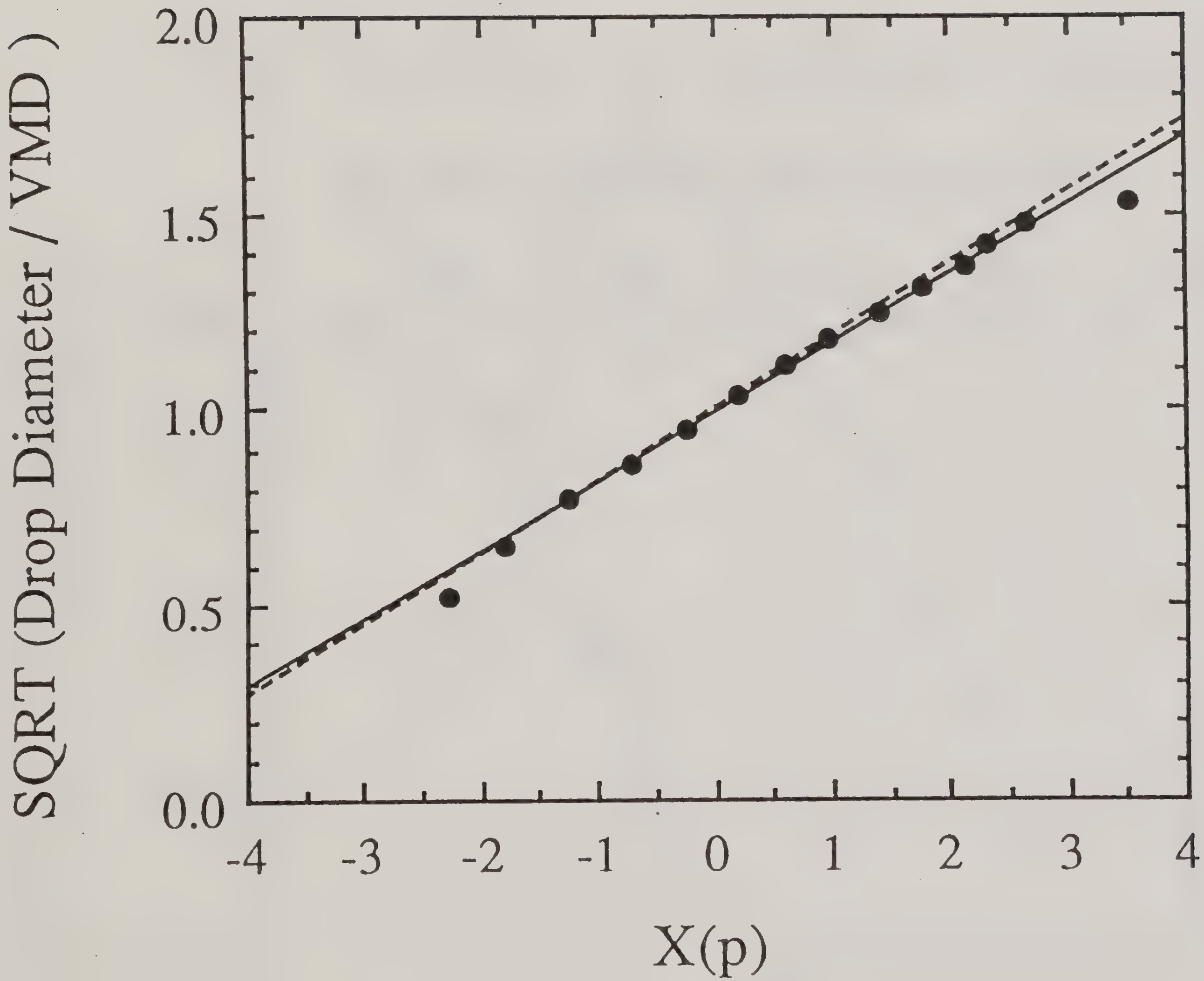


Figure 5. Normal probability representation of the drop size distribution given in Figure 1, plotted against the square root of the drop diameter. $X(p)$ is such that at $X(p) = 0$ the probability is 0.5 . The solid line is the least squares fit; the dashed line maximizes the common area in Figure 6.

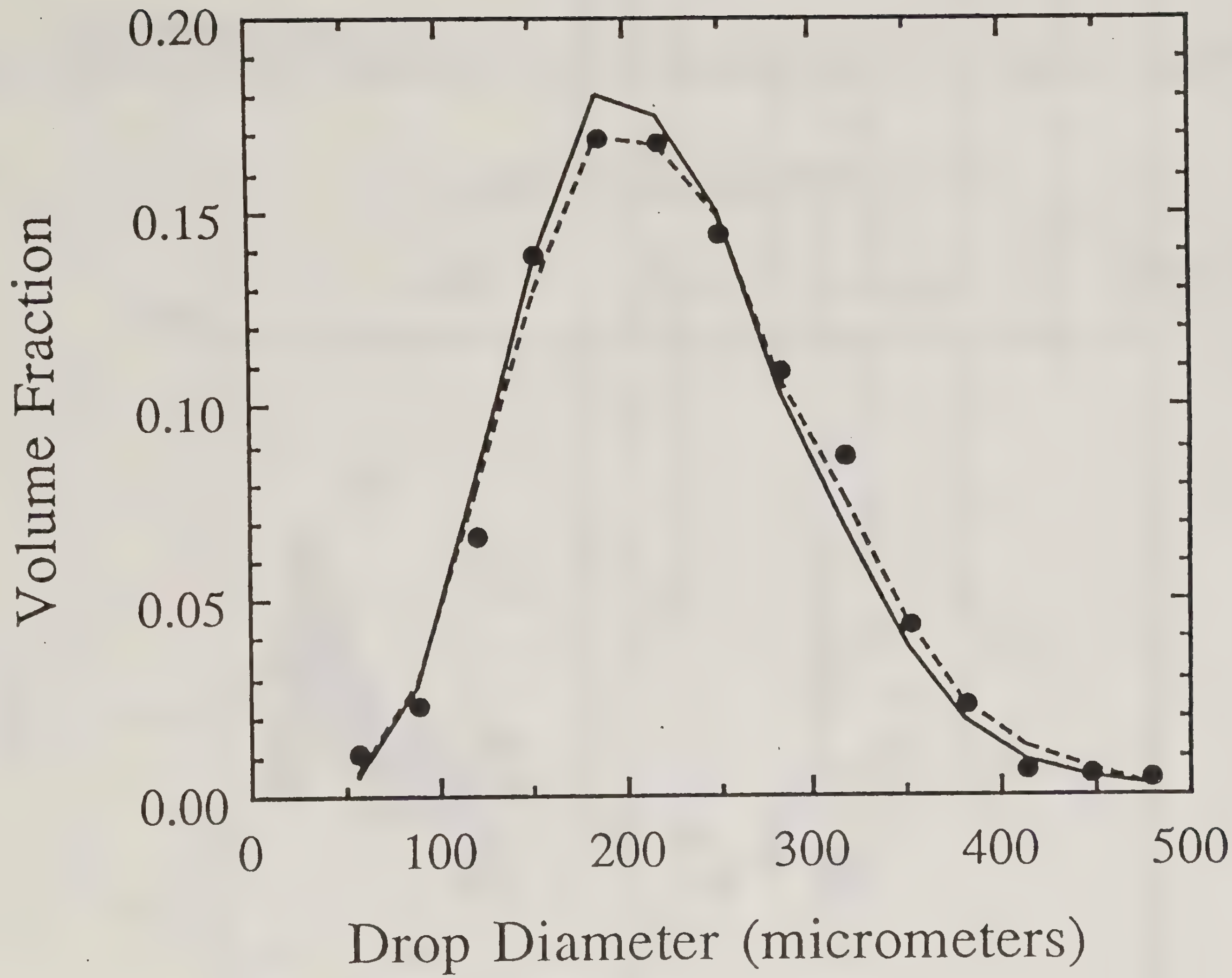


Figure 6. Corresponding drop size distribution by volume fraction for the curve fits from Figure 5.

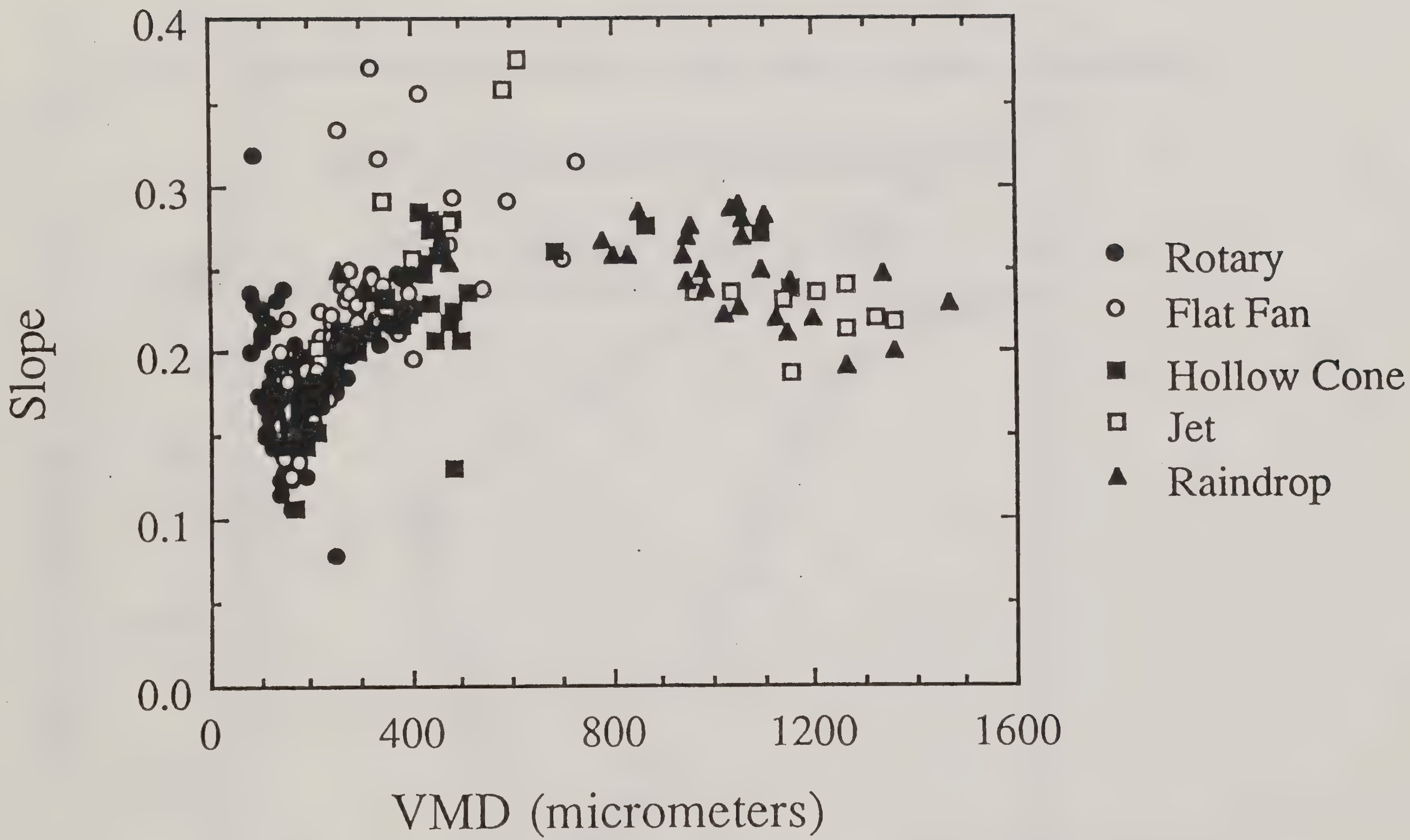


Figure 7. All drop size data correlated with the normal probability approach and reduced to VMD and Slope values typical of that shown in Figure 5.

Problems

It's not all fun and games. Some of the unsolved FSCBG problems are:

Along-wind flight lines

Upwind deposition (turning the flight lines on and off)

Canopy top deposition

Far downwind drift, especially with:

New Zealand (Richardson) data
U. S. Army Real Time Volume Source Model
Dow Elanco data

-- calling into question the accuracy of FSCBG far downwind (the prediction of less than 0.5 percent of the released mass) -- an ongoing concern at this time.

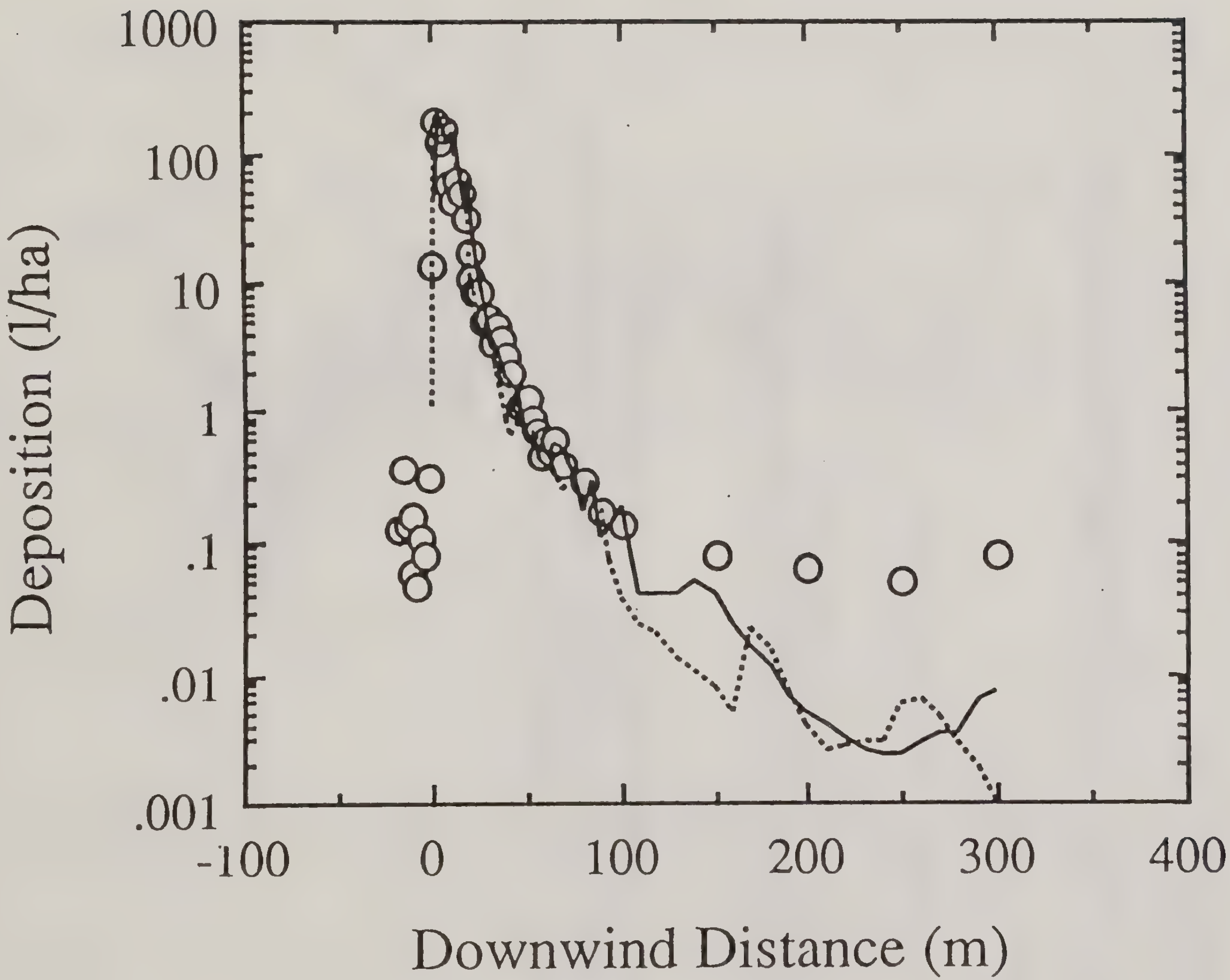


Figure 1. FSCBG comparison with the Richardson field data (circles): original prediction (dashed curve); twenty percent increased wind speed (solid curve).

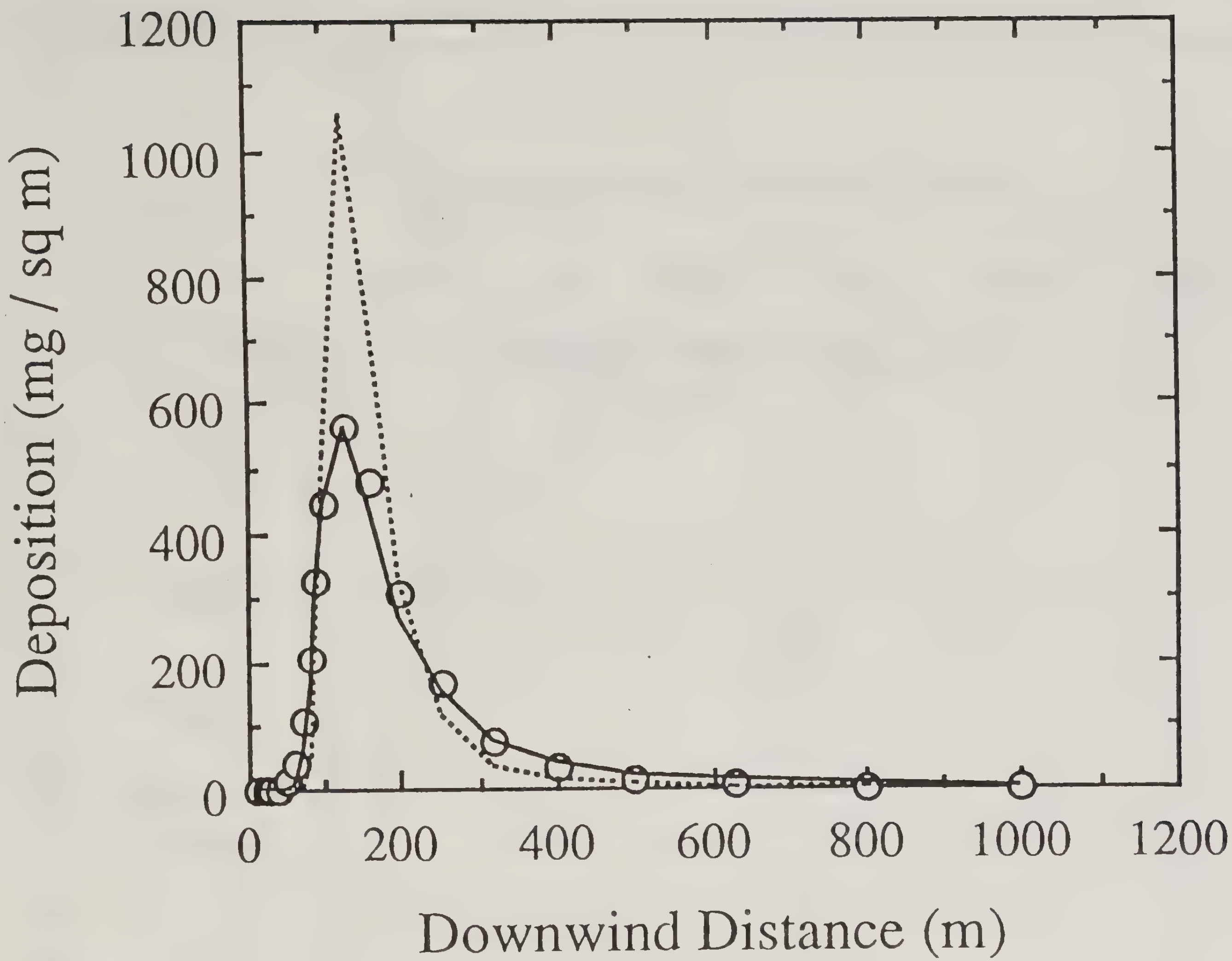


Figure 3c. Comparison of deposition predictions between RTVSM (circles) and FSCBG 3.0/3.05 (dashed curve) and 4.0 (solid curve) for a 100 micrometer drop size.

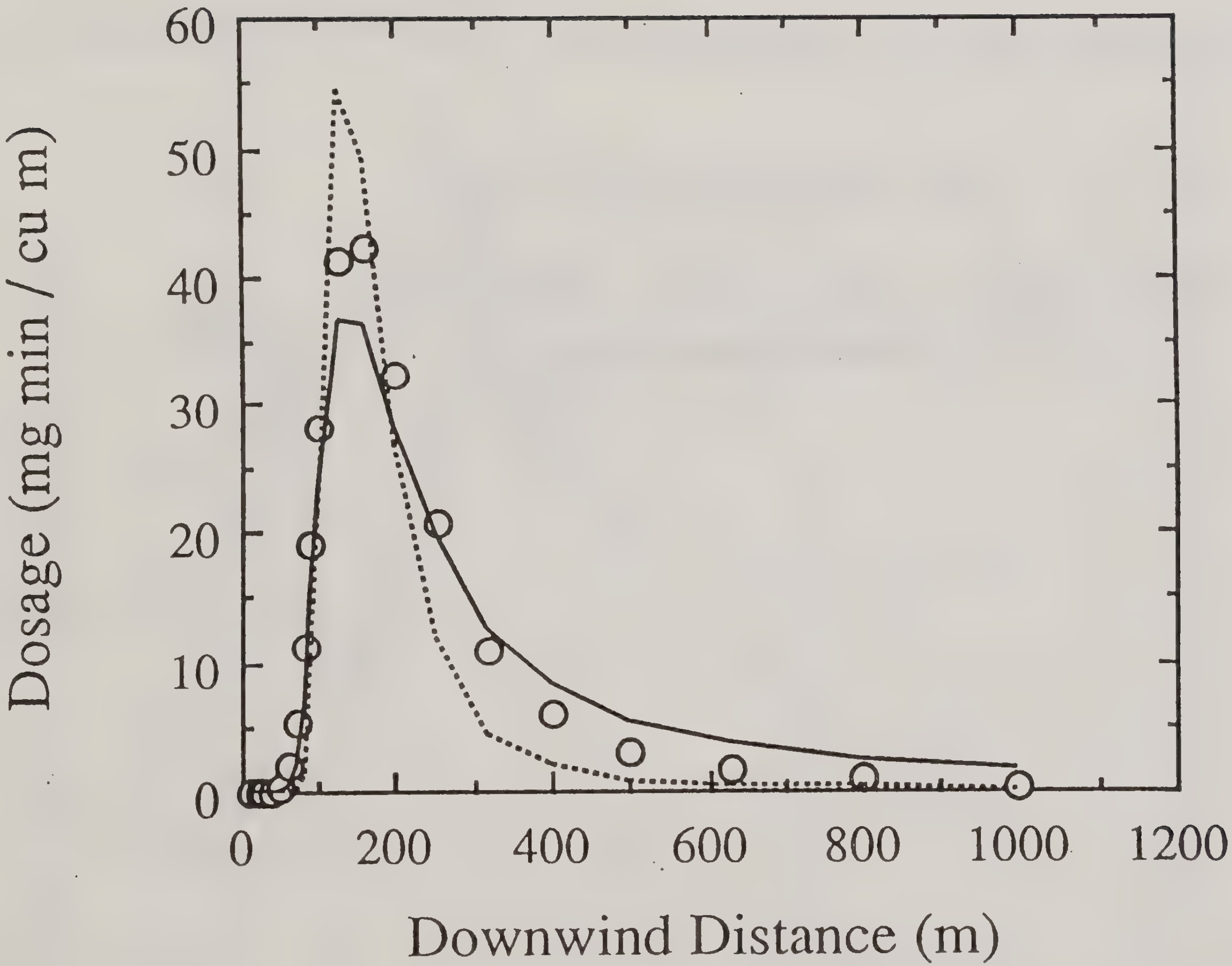


Figure 2c. Comparison of dosage predictions between RTVSM (circles) and FSCBG 3.0/3.05 (dashed curve) and 4.0 (solid curve) for a 100 micrometer drop size.

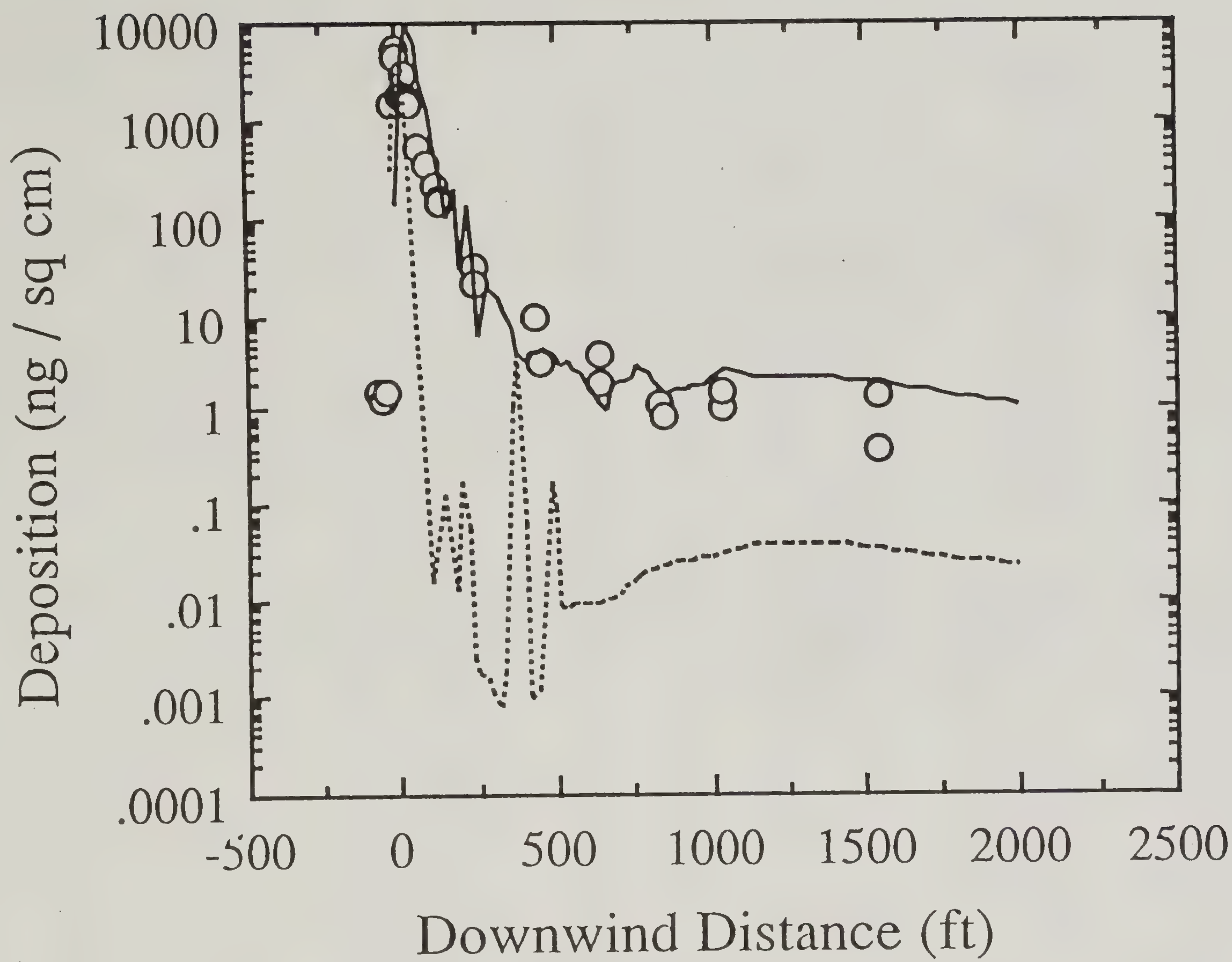


Figure 5a. Comparison of FSCBG original predictions (dashed curve) and extended predictions (solid curve) with the drop size data of Dow Elanco Treatment A (circles).

Other Topics

Other anticipated tasks:

Property estimation for evaporation modeling
Statistically averaged quantification
Further validation studies
Possible training session in Australia 1993

Supported the Spray Drift trials in complex terrain near Salt Lake City -- developing a series of programs to reduce data and interpret FSCBG predictions:

METDAT -- analyze Ekblad met tower data
SPREAD -- develop spread factor correlation
ASCAS -- interpret drop size image analysis results

-- results will be reported in ASAE preprint 921085.

Technical interactions with: Al Womac, Scott Cameron, Dave Miller

Spray Drift Task Force involvement

U. S. Air Force Fuel Dumping contract

Dave Whiteman

Battelle
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June 26, 1992

Dr. Jack Barry
Program Manager
Forest Pest Management
USDA Forest Service
2121C, 2nd Street
Davis, CA 95616

Dear Jack:

Attached are two items related to the 3rd National Spray Model Advisory Committee meeting held in Charlotte, North Carolina, on June 23, 1992. First is the written report of the Meteorology Committee. Second is a summary of my oral presentation at the meeting regarding a new technique that may prove helpful in predicting the influence of upper-air pressure systems on wind circulations inside valleys.

Thanks again for the invitation to be a member of the committee and the opportunity to participate in the Charlotte meeting. I especially enjoyed having the chance to discuss interesting technical issues with some of the other participants.

Sincerely,

Dave White

C. David Whiteman
Staff Scientist
Atmospheric Physics Group
ATMOSPHERIC SCIENCES DEPARTMENT

CDW:rak

Enclosures

Charlotte Meeting, June 23, 1992
Meteorology Committee Report

C. D. Whiteman

A. Meteorology Committee Charter

"Develop recommendations on field meteorological measurements (types, frequency, numbers, and location) for input to computer models for validation and evaluation, and for operational use in forestry and agriculture."

B. Committee Membership

Dave Whiteman
Bob Ekblad
Jim Rafferty

C. Report

The committee got together through phone conversations in June 1992. Bob Ekblad provided an excerpt from the Spray Drift Survey Data Base RFP which lists the meteorological parameters that will be used to compile a summary of spray drift data from past field programs. The meteorological parameters to be included in this data base are as follows:

General Information

- averaging period for met data
- heat flux
- height, Monin Obukhov length
- u^*

Specific Profile Data

- number of levels, heights of measurements
- ambient temperature and relative humidity
- wind sensor type, wind speed and direction
- turbulence sensor type, sigma w and sigma v

We began our task by considering this set of meteorological measurements as a straw man. The list of measurements seemed adequate for some purposes but inadequate for others. Further, it seemed to include requirements for some data that would be very

difficult to meet in other situations (e.g., small remote spray blocks). Upon further consideration we felt that the scope of the committee's charter was too broad and that the types of supporting meteorological measurements would depend greatly on the actual scope of the spray project or modeling or observational programs to be conducted. Detailed meteorological measurements would be necessary to support the evaluation of particular modules (e.g., a turbulence module) in AGDISP or FSCBG, while an isolated back country spray block application would be unable to support the array of meteorological equipment that would be necessary for a typical spray block application. The meteorological equipment necessary to support "operational use in forestry and agriculture" would depend greatly on the detailed needs of the particular project . Further, while onsite meteorological equipment would clearly be within the scope of the committee's purview should we include recommendations on necessary synoptic-scale meteorological support, say, from a National Weather Service Forecast Office?

Since we did not have time to resolve these questions before the Charlotte meeting we concentrated efforts on monitoring new meteorological measurement technologies, as follows:

- Doppler Minisodar

  Mini-sodars and radar profilers are remote wind sounding systems. The Doppler minisodar seems well-suited for use in monitoring wind profiles for aerial spraying operations since it can sound to 150 m depths and is portable. The continuous wind data provided would be useful for predicting drift. Another device for remote sensing of temperature profiles needs to be developed in order to meet needs for stability information. This is presently an active area of research. Remote Acoustic Sounding Systems (RASS) can provide this information at radar profiler locations but we need a device that has good vertical resolution in the near ground layers.

- RF modems

  The U.S. Forest Service and other organizations have been using RF modems to transmit data from remote field meteorological stations based on short towers. The Campbell Scientific, Inc., stations have performed well, in general, and provide the means to relay data from multiple stations to a central location where a phone modem is available.

- Cellular Phones

  As cellular phone coverage of the U.S. has improved, the U.S. DOE and other groups have begun using cellular phones to upload data from remote weather stations. In many cases this method has advantages over dedicated phone lines, as the installation costs are low.

- The Global Positioning System

  Hand-held units can help determine the exact location of field sites and to monitor and record the positions of spray aircraft. This last task would provide important information with respect to spray drift source modules.

  Battelle is presently using a Magellan GPS printed circuit board as the navigation system on a remotely piloted vehicle and initial testing has been successful, although flight tests of the GPS have not yet begun.

D. New Committee Assignments

Harold Thistle and Dave Miller agreed to assignments on the Meteorology Committee, and will assist in drafting a more comprehensive committee report on meteorological measurements for the next annual meeting.

Summary of Presentation
National Spray Model Advisory Committee

C. D. Whiteman
June 23, 1992

Discussion of complex terrain meteorology issues at the Blacksburg meeting in 1991 focused on the influence of thermally developed circulations on spray drift, with emphasis on slope and valley winds. Most of the examples were from western U.S. valleys.

The presentation at the 1992 Charlotte meeting was focused on valleys in the climatological setting of the U.S. Southeast and investigated the influence of larger scale atmospheric circulations above a mountain range on the flows that would develop within valleys.

Four hypothetical mechanisms were offered to explain how within-valley flows might be affected by above-valley flows. The mechanisms included thermal circulations, downward momentum transport, forced channeling, and pressure driven channeling. An investigation of winds in the Tennessee Valley showed that winds within the valley are bi-directional--with flows either up or down the valley's axis. A climatological analysis showed that these bi-directional flows are not generally caused by thermal circulations, downward momentum transport, or forced channeling. Rather, they appear to be caused predominantly by pressure driven channeling, where the valley flow is driven by the along-valley component of the near-ridge-top horizontal pressure gradient. In extreme cases this mechanism can produce "counter-currents," in which the upper flows blow in opposition to the direction of flows within the valley. Since the pressure gradient aloft can be forecast with some accuracy, the verification of this mechanism raises the possibility that valley wind directions could be forecast accurately, especially when pressure gradients are moderate or stronger. Such a forecast scheme could be useful to support aerial spray projects in eastern U.S. valleys. The mechanism will be investigated further to see if a means can be determined to integrate understanding of this mechanism with understanding of the thermal circulations that are present in the western U.S. so that a hybrid forecasting scheme might be developed to support western U.S. spraying operations.

Appendix D

Professional Papers

Paper No. 921084
AN ASAE MEETING PRESENTATION

SPRAY DRIFT ATTRIBUTES OF HIGH–PERFORMANCE AIRCRAFT AT VARYING VELOCITY OVER COTTON FOLIAGE

by

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Written for presentation at the
1992 International Summer Meeting
sponsored by
THE AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS

Charlotte, North Carolina
June 21-24, 1992

SUMMARY:

The downwind spray drift resulting from a turbine-powered, fixed-wing aircraft was investigated using high-volume air samplers in a cotton field. Aircraft velocity treatments of 218, 241, and 265 km/h were analyzed using cinnamyl alcohol tracer quantified by gas chromatography. Results indicated no significant differences at individual stations up to a distance of 67 m. Drift from the 218 km/h treatment was significantly greater than that from the 241 and 265 km/h treatments at individual stations at distances ranging from 79 to 201 m. Strength of wingtip aerodynamic vortex decreased with increasing aircraft velocity and offset the drift potential from decreased droplet size.

KEYWORDS:

Aerial sprays, Agricultural aircraft, Agricultural chemicals, Agricultural pesticides, Air sampler, Airspeed, Drift, Droplet sizes, Tracers

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Spray Drift Attributes of High-Performance Aircraft at Varying Velocity Over Cotton Foliage

A.R. Womac[1], J.E. Mulrooney[2], and L.F. Bouse[3]

Abstract

The downwind spray drift resulting from aerial application was investigated using high-volume air samplers in a cotton field. A turbine-powered, mono-winged aircraft was operated at 218, 241, and 265 km/h over a 700-m flightline oriented 23.6° from a 610-m sampler line. Results using cinnamyl alcohol tracer, quantified by gas chromatography, indicated that concentrations collected from air sampler filters were not significantly ($P<0.05$) different for all velocity treatments at individual stations up to a distance of 67 m from the flightline center. Drift from the 218 km/h treatment was significantly ($P<0.05$) greater than that from the 241 and 265 km/h treatments at individual stations from 79 to 201 m. Wind velocity ranged from 1.65 to 3.34 m/s. Spray droplet volume median diameters were 247, 218, and 189 μm for the velocities of 218, 241, to 265 km/h, respectively. Volume of spray in small droplets less than 125 μm increased from 3.53 to 16.17% as velocity increased. The strengths of wingtip aerodynamic vortex of the 241 and 265 km/h treatments, compared to that for 218 km/h, decreased by approximately 10 and 22%, respectively, thereby offsetting the potential drift corresponding to a decrease in droplet size of 12 and 23%. Predictions by a spray drift model indicated a nearly uniform response in total airborne spray concentration versus distance among the three aircraft velocities.

Keywords: Aerial sprays, Agricultural aircraft, Agricultural chemicals, Agricultural pesticides, Air sampler, Airspeed, Drift, Droplet sizes, Tracers.

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[2] Entomologist, USDA-ARS, Application Technology Research Unit, Stoneville, Mississippi.

[3] Research Leader, USDA-ARS, Aerial Application Research Unit, College Station, Texas.

Introduction

Agrichemical spray drift from a target zone does not benefit the protection of crops and can lead to toxic side effects on non-targets. Field drift studies have documented the movement characteristics of many agrichemical sprays, including carbaryl (Currier et al., 1982); fenitrothion (Crabbe et al., 1980); fenvalerate (Sanderson et al., 1986); glyphosate (Yates et al., 1978); and 2,4-dichlorophenoxyacetic acid (2, 4-D) (Huitink et al., 1990). Drift of these and other agrichemicals can be reduced by selecting proper application techniques and equipment for the specific conditions. This is especially true for aerial application that is subject to a wide array of spray-affecting variables.

Advancements in fixed-wing, agricultural aircraft design have resulted in the use of high-performance turbine engines, such as the Pratt & Whitney PT-6 (Pratt & Whitney Canada Inc., Longueuil, Quebec) and the Garrett TPE-331 (Garrett Air Research, Pheonix, Arizona). The increased demand for these aircraft was exemplified by Snow (1991) who reported that turbines were supplied on two-thirds of the new aircraft manufactured by Air Tractor, Inc. (Olney, Texas). Compact turbine size allows for reduced aerodynamic drag through decreased frontal area, which leads to increased aircraft velocity. Piston-powered agricultural aircraft typically spray at velocities ranging from 170 to 220 km/h. Barry et al. (1978) evaluated a turbine conversion of the Rockwell Thrush Commander (Ayers Corp., Albany, Georgia) fitted with a Garrett TPE-331 engine, and reported velocities of 241 and 256 km/h at 60 and 70% power levels, respectively, at sea level.

McWhorter (1991) reported that the effect of aircraft velocity on spray drift was the number one priority established by researchers in an April 1991 meeting. Aircraft velocity is important because it influences the drift of released airborne spray material by two mechanisms: (1) atomization and (2) aircraft wake.

Bouse (1991) examined the droplet size spectra produced by nozzles commonly used on fixed-wing aircraft. He determined that increased relative velocity of the spray discharge with respect to the airstream reduced droplet volume median diameter and significantly increased the production of droplets in the size range of <200 μm. Increased aircraft velocity increases the relative velocity of spray from nozzles typically angled back and discharging spray at velocities less than that of the aircraft. This increased velocity can increase the potential for drift through decreased droplet size. The exact effect of aircraft velocity on

droplet size depends upon aircraft velocity, spray discharge velocity, nozzle orientation, and spray pattern.

The aircraft wake affects the trajectory of droplets primarily with vortices generated at the wingtip (Quantick, 1985). Teske (1992) reported that the strength of wingtip vortex circulation for an aircraft flying at constant altitude is approximated as the aircraft weight divided by the product of aircraft velocity, air density, and twice the aircraft semispan. Increased aircraft velocity generally decreases vortex strength and can lead to decreased drift potential. It should be noted that this decreased potential may be overridden by canopy parameters, aircraft height, placement of nozzles, droplet size, meteorological conditions, and other factors.

Objectives

The overall research objective was to determine the spray drift resulting from aerial application using a turbine-powered, fixed-wing aircraft operating at the velocities of 218, 241, and 265 km/h. Specific objectives were to determine: (1) spray atomization characteristics, (2) field-monitored spray drift characteristics, and (3) model-predicted spray drift characteristics.

Equipment and Methods

Aircraft and Spray Equipment

A Turbo-Thrush S2R aircraft (Ayers Corp., Albany, Georgia) equipped with a Pratt & Whitney PT-6-41 turbine engine was employed for the drift tests. The engine was originally rated at 634 kW and had been derated to 559 kW. The relative amount of propeller shaft torque, indicated by a pressure gage, had a maximum value of 469 kPa at 559 kW. Mean aircraft velocities (groundspeeds) of 218, 241, and 265 km/h were determined by calibrated radar for the three torque gage readings of 207, 276, and 345 kPa, respectively. These settings produced propeller shaft input power levels of approximately 247, 329, and 412 kW, respectively. Minor differences between groundspeed and airspeed may have occurred due to flight direction with respect to wind direction and velocity.

In this experiment, the velocity (groundspeed) of the aircraft was considered a treatment. Applications were made at 218, 241, and 265 km/h (Table 1) at approximately 3.7 m boom height above the cotton canopy. Height was monitored by photography and by visual estimates from the

ground. Height adjustments resulting from visual monitoring were communicated to the pilot on a pass-to-pass basis. The aircraft had a conventional aerodynamically streamlined boom with 50 D6-46 tips (Spraying Systems Co., Wheaton, Illinois) on Type 4664B diaphragm check valve nozzle bodies oriented 45° down and back. Nozzles were operated at a boom hydraulic pressure of 207 kPa for all tests. Outer nozzles were at 70% of the wingspan. Spray swath was approximately 15.5 m. Total spray rates were approximately 28, 25, and 23 L/ha for aircraft velocities of 218, 241, and 265 km/h, respectively. Nozzle selection and operating pressure were constant for all velocity treatments.

Spray Drift Tracer

Cinnamyl alcohol (3-phenyl-2-propene-1-ol) was selected as a tracer to quantify the downwind spray drift and it proved to be an essential component of the research. It was selected because it is non-toxic to humans, soluble in water and ethanol, relatively inexpensive, detectable at low levels (0.1 ppm), stable under field conditions, non-staining to cotton fiber, and does not conflict with crop/agrichemical label restrictions. No crop injury to cotton plants was observed. The tracer solution consisted of 1.32% (v/v) cinnamyl alcohol (I-Mart, Fair Lawn, New Jersey) and 0.25% (v/v) of X-77 spreader (Valent U.S.A. Corp., Walnut Creek, California) in tap water.

Cinnamyl alcohol residues were removed from air sampler filters using ethanol. Residues were analyzed without cleanup using a Hewlett-Packard 5890A gas chromatograph equipped with a flame ionization detector. An auto-injector introduced 2 μL samples into the inlet. A 0.32 mm x 25 m methyl silicone gum column was used to separate peaks. Quantification was by peak area. Temperatures (°C) were: column - 200, detector - 300, and inlet - 200. The run was isothermic with a total gas flow of 393 ml/min and a retention time of 3.65 min.

Droplet Size Analyses

Droplet size analyses were conducted using the aircraft nozzle test facility described by Bouse and Carlton (1985). A laser-imaging spectrometer (Particle Measuring Systems, Inc., Boulder, Colorado) with an OAP-2D-GA1 probe measured the droplet size spectra of the spray output from a nozzle mounted in a high-speed airstream. Droplet sizes were measured at the same air velocity treatments using the nozzle, orientation, and operating pressure used in the field drift study. Measurements were obtained by traversing the probe through the spray at the heights of 1/8,

3/8, 5/8, and 7/8 of the spray plume at a distance 76 cm downwind from the nozzle (Bouse, 1991). Measurements from all heights were combined to give a single droplet spectrum for each spray plume tested. Test measurement for each treatment was replicated three times.

A solution of 1.32% (v/v) cinnamyl alcohol and 0.25% (v/v) of X-77 spreader in tap water was tested. Dynamic surface tension (SensaDyne) of this solution ranged from 35.7 dynes/cm (31.90 °C, 5.37 bubbles/s) to 45.6 dynes/cm (26.50 °C, 0.17 bubbles/s). Static surface tension (DuNouy ring) was 36.38 dynes/cm. Viscosity (Brookfield with UL adapter) was approximately 1.0 mPa s. Specific gravity measured with a hydrometer was 0.998 at 25.6 °C.

Also, droplet sizes of solutions of tap water and 0.25% (v/v) X-77 spreader, tap water and 0.1% X-100 (v/v) surfactant (Rohm and Haas Co., Philadelphia, Pennsylvania) and tap water were compared. Dynamic surface tension ranged up to 71.80 dynes/cm for water at 27.30 °C (0.52 bubbles/s).

Spray Drift and Meteorological Instruments

Fifteen Staplex Model TFIA high volume air samplers (Staplex Air Sampler Division, Brooklyn, New York), mounted on 1.8-m high supports, were spaced 30.5 m along a sampler line (Fig. 1). Perpendicular distance from each flightline to samplers ranged from 30.5 to 201.2 m in constant increments of 12.2 m. Each sampler was operated with a Staplex Model TFA2133 (102-mm diameter) glass fiber filter at a mean air volume rate of 1.23 m^3/min.

Two 10-m meteorological towers mounted on trailers were equipped with instruments and parked along the sampler line. Cup-type anemometers and vane-type wind direction sensors (Met One, Inc., Grants Pass, Oregon) were mounted at the heights of 5.0, 7.5, and 10 m. Thresholds were 0.45 and 0.447 m/s for velocity and direction sensors, respectively. A Gill UVW propeller anemometer and UVW Translator (R.M. Young Co., Traverse City, Michigan) were positioned at a height of 2.5 m and had a threshold of 0.3 m/s. Temperature sensors (Campbell Scientific, Inc. Logan, Utah) were placed at the heights of 2.5, 6.2, and 10 m and had an accuracy of 0.4 °C. A relative humidity sensor (Campbell Scientific, Inc. Logan, Utah) was located at a height of 1.5 m and had an accuracy of 2%. A pyranometer (Li-Cor, Inc., Lincoln, Nebraska), mounted at a height of 10 m, measured solar irradiance up to 1 kW m^{-2}.

All meteorological sensors were connected to a Campbell 21X Micrologger (Campbell Scientific, Inc., Logan, Utah) that monitored sensor outputs at 5 s intervals and logged summary statistics at 1 min. intervals. Data were downloaded through storage modules and software to a personal computer for analyses.

Mean meteorological conditions recorded during each test run are summarized in Table 1. Mean ambient air temperature and relative humidity ranged from 27.8 to 31.2 °C and from 55.4 to 64.5%, respectively. Wind velocity ranged from 1.65 to 3.34 m/s with the coefficient of variation ranging from 16.6 to 47.9 %. The lowest mean velocity had the highest coefficient of variation. Wind direction is reported as the included angle between the wind vector and the sampler line. Wind direction ranged from 44.3 to 96.3° with the coefficient of variation ranging from 14.2 to 113.4%. The lowest mean wind velocity also had the highest direction coefficient of variation. The stability ratio (SR) (Quantick, 1985), computed from mean air temperatures and velocity conditions during each run, varied throughout the test and ranged from unstable (-1.32) to very stable (1.87). The overall SR mean for the test was neutral (-0.16). It should be noted that SR was computed using temperature sensors that had a degree of accuracy of 0.4 °C, which was marginal accuracy for computing this factor.

Spray Drift Test Procedures

Drift tests were conducted in a 1.61 by 1.61 km flat cotton field essentially free from any obstruction to the wind. The field had mature cotton plants. The field setup consisted of two flightlines and a sampler line arranged with a constant included angle (23.6°) between each flightline and the sampler line (Fig. 1). Flightline 1 (Fig. 1) was setup and used for Runs 1-5 (Table 1) until shifting winds required the setup of Flightline 2 for Runs 6-12.

The aircraft velocity treatments were replicated four times, in a randomized complete block design, and were identified as twelve runs (Table 1). Each run consisted of four aircraft passes applying spray along the 700-m flightline. The pilot alternated the direction of flight from pass to pass. Air samplers were started at the beginning of the first pass and were continuously operated until 5 min. elapsed after the end of the fourth pass. Air sampler operation averaged 8.9 min. and ranged from 7 to 11 min. Meteorological data, obtained during the same time interval as air sampler operation for each run, were selected for analyses.

Treated air filters were placed in plastic sample bags, immediately placed on ice in a cooler, stored in a laboratory freezer, and then analyzed for cinnamyl alcohol using a gas chromatograph. Results are expressed as concentration (ppm) of cinnamyl alcohol in 10 ml of solvent.

Spray Drift Data Reduction Techniques

Cinnamyl alcohol residue data were sorted by replication, aircraft velocity treatment, and the perpendicular distance between the flightline and sampler. Residue data for 241 and 265 km/h treatments were corrected for a rate of 28 L/ha because varying velocity resulted in different application rates. Data were not adjusted for percent recovery based on the sampler collection efficiency and losses of tracer through the sampler. Separate tests of spiking known amounts of tracer on the sampler filter indicated a nearly constant percentage of loss through the air sampler for applications ranging in volume from 1 μL to 1000 μL. Losses ranged up to 95%. However, comparisons between treatments should be valid since drift samples were uniformly subjected to essentially the same sampler and handling conditions.

Analysis of variance (SAS, 1992) was performed using the log of corrected cinnamyl alcohol concentration with and without the covariants of mean wind velocity, wind direction, cosine of wind direction, temperature, stability ratio, relative humidity, sampler operation time, and initial hopper load. The analysis using log of concentration versus distance between samplers and flightline gave the same mean separation as that without the log transformation. However, the log-linear function did more closely approximate the form of the trend between concentration and distance. This was used in regression equations of rinsate concentration versus distance to predict concentrations at the different sampler distances. Results expressed herein are actual values determined using the antilog transformation.

FSCBG Spray Drift Prediction

The aircraft and meteorological conditions for each test were input into the spray drift model FSCBG, Version 4.01 (FSCBG, 1992). Selected input variables are reported (Table 2). Computations were conducted using near wake and evaporation models selected. The concentration model was also selected because the airborne component of spray was monitored with the air samplers in the field study. Aircraft specifications from the Turbo-Thrush manufacturer (Ayers Corp., Albany, Georgia) were used. The maximum number of nozzles (20) allowed by the model was evenly spaced

across the simulated boom, within the middle 70% of the wingspan. Droplet size spectra obtained at the aircraft nozzle test facility were converted to 16 categories of mass fraction based on average diameter. Water was considered as the only significant volatile fraction of the spray mixture. A single aircraft pass along the flightline at 113 L/ha was used to simulate the four passes in the field at 28 L/ha. The last five variables in Table 2 were assumed based on typical atmospheric conditions.

Results

Droplet Size Analyses

The effect of increasing the air velocity from 218 and 241 km/h to 265 km/h caused the volume median diameter ($D_{v0.5}$) of spray droplets to decrease from 247 and 218 μm to 189 μm, respectively, for the spray solution of water, 1.32 % (v/v) cinnamyl alcohol, and 0.25 % (v/v) X-77 surfactant (Table 3). Increased air velocity resulted in a nearly linear decrease in $D_{v0.5}$ ranging from 11.7 to 23.5% less than that for the 218 km/h treatment. The spray volume in droplets less than 125 μm in diameter significantly increased from 3.53 and 7.73% to 16.17% for the increase in velocity from 218 and 241 km/h to 265 km/h, respectively.

Air velocity had a similar effect on the spray mixture of water and 0.1% (v/v) X-100 surfactant, which had $D_{v0.5}$ values decrease from 298 and 269 μm to 253 μm as velocity increased from 218 and 241 km/h to 265 km/h, respectively. Increased air velocity resulted in a decrease in $D_{v0.5}$ ranging from 9.7 to 15.1% less than that for the 218 km/h treatment. The spray volume in droplets less than 125 μm in diameter increased from 0.90 and 1.57% to 2.30%, which was approximately 14% of that for the cinnamyl alcohol solution at the highest velocity.

The cinnamyl alcohol component of the solution resulted in the production of small droplets. For a constant air velocity of 241 km/h, the sprays of water alone, water plus X-77, and the solution of water, X-77, and cinnamyl alcohol produced $D_{v0.5}$ values of 278, 265, and 218 μm, respectively. The volume of spray in droplets less than 125 μm in diameter was 1.17, 1.63, and 7.73 % for the three mixtures.

As air velocity increased, relative span (RS) increased from 0.75 to 0.99 for the mixture of water, X-77, and cinnamyl alcohol, and increased from 0.73 to 0.83 for the mixture of water and X-100. The increase in RS may be attributed to a decreasing $D_{v0.5}$ value in the denominator of RS.

Field Spray Drift

The mean concentration of the 218 km/h treatment rinsate was 2.46 ppm, which was more than twice the amount of cinnamyl alcohol found on either the 241 or 265 km/h treatment filters (Table 4). The mean concentrations of the two highest velocity treatments were not statistically different ($P<0.05$) from each other based on the least significant difference (LSD) test of the log transformed concentrations. Reported means and LSD values are actual values determined by taking the antilog of the analysis results (Table 4).

The rinsate concentrations predicted by regression for velocity treatments at individual sampler stations were not significantly different ($P<0.05$) up to a distance of 67 m (Table 6). Distance was defined from the center of the flightline to the air sampler and along a line perpendicular to the flightline. The cinnamyl alcohol concentrations from the 241 and 265 km/h treatments at individual sampler stations were numerically similar at distances from 79 to 201 m and asymptotically approached zero concentration at a rapid rate (Fig. 2). However, they were significantly ($P<0.05$) less than that from the 218 km/h treatment (Table 6).

We initially suspected that the airborne cinnamyl alcohol was evaporating during drift tests and subsequently conducted laboratory tests of various solutions, including pure cinnamyl alcohol. Ten milliliter solutions of distilled water; water and 1.32 % (v/v) cinnamyl alcohol; water, 0.25 % (v/v) X-77 surfactant, and 1.32 % (v/v) cinnamyl alcohol; and pure cinnamyl alcohol were placed in 17.5 mm i.d. vials. Gravimetric determinations of these four treatments, replicated four times, were conducted prior to long-term storage in an oven maintained at 32 °C, and at intervals of at least daily for one week. The mean losses from the above treatments were 191.0, 195.6, 197.1, and -7.3 mg, respectively, over the one-week interval. The cinnamyl alcohol alone did not appear to volatilize and may have behaved hygroscopically. For vapor pressures of 1, 10, 40, 100, 400, and 760 mm of mercury, corresponding temperatures for cinnamyl alcohol are 72.6, 117.8, 151.0, 177.8, 224.6, and 250.0 °C, respectively (Weast, 1989). From these results, we expected no significant loss of cinnamyl alcohol from evaporation.

The strengths of wingtip aerodynamic vortex of the 241 and 265 km/h treatments, compared to that of the 218 km/h treatment, theoretically decreased by approximately 10 and 22%, respectively. This comparison assumes a constant aircraft weight, aircraft semispan, air density, and that the aircraft flies at constant altitude. We observed that the

magnitude of decrease in vortex strength (10 and 22%) is nearly identical to the magnitude of decrease in $D_{v0.5}$ (11.7 and 23.5%). The decrease in vortex strength reduces drift potential that subsequently offsets the increase in drift potential from decreased droplet size. It is difficult to ascertain the exact compensation in reduced drift potential that can be credited to decreased vortex strength versus the increased potential of decreased droplet size. Apparently, the combined effect of vortex strength and droplet size resulted in the field treatment differences. The vortex effect was critical at the aircraft velocity of 218 km/h.

The covariant analysis determined that all covariants, including mean wind velocity, wind direction, cosine of wind direction, temperature, stability ratio, relative humidity, sampler operation time, and initial hopper load, did not significantly ($P<0.05$) account for test variability.

We observed that test replication affected the value of mean rinsate concentration (Table 5). All four replications were significantly different from each other for $P<0.05$. The value of concentration was 0.77, 1.24, 1.93, and 2.91 ppm for replications 1-4, respectively. These concentrations increased at the rate of 61, 56, and 51% greater than the preceding concentration. Air samplers were always approached from the downwind direction to reduce inadvertent contamination of air filters. Also, full agitation of the cinnamyl alcohol solution contained in the aircraft hopper should have reduced any stratification and possible effect on the concentration sprayed from replication to replication. If settling had been a problem, concentration would have possibly decreased since cinnamyl alcohol has a specific gravity of 1.044.

FSCBG Drift Prediction

The FSCBG spray drift model predicted a nearly uniform response in total airborne spray concentration versus distance, for the aircraft velocities of 218, 241, and 265 km/h (Fig. 3). Data in Fig. 3 are averages of concentration predicted for individual runs using input data specific for each run. Input data were not averaged over individual runs for input into the model.

Specific model prediction curves for total concentration versus distance were determined for each test run and are sorted by the aircraft velocities of 218 (Fig. 4), 241 (Fig. 5), and 265 km/h (Fig. 6). On these same graphs the rinsate concentrations obtained from the field were plotted. The FSCBG total concentration and the rinsate concentration are not directly comparable since each is based on different measurement types

and units. However, the trends in concentration with distance should be comparable since the two concentrations should vary only by a constant factor.

The model tended to predict high concentrations close to the flightline and low concentrations at distances greater than 100 m (Figs. 4-6). Concentration values nearest the flightline ranged from about 6.5 to 33 mg/m^3. The model predicted a sharp decline in total concentration between the flightline and the 100 m distance. Concentration values at 100 m ranged from approximately 0.5 to 2.5 mg/m^3. Predicted concentration generally approached zero at a distance of 200 m.

FSCBG predictions for Run 1 (Fig. 4), Run 2 (Fig. 5), Run 3 (Fig. 6), Run 5 (Fig. 5), and Run 6 (Fig. 6) had trends similar to that of the observed field data. Monitored variables apparently had little effect on whether the predicted trend was close to the field data. For example, the angle between the wind and the flightline varied from 67.9 to 119.9°. The accuracy of the predicted concentrations did not correlate with the amount of wind angle deviation from the ideal 90°. High concentration predictions for distances up to 50 m for Run 9 corresponded with the highest mean wind velocity of 3.34 m/s. It should be noted that the graph scales for Run 9 were much greater than those for the other graphs in Fig. 6.

Much unexplained variability was observed in field data. For instance, the drift depicted in Run 12 (Fig. 6) is greater than that for Run 3 (Fig. 6). Both runs were conducted at 265 km/h and had similar mean wind velocities of about 2.5 m/s. The unexplained variability for these two particular runs was that Run 12 was conducted at a low hopper load (95 L) and Run 3 was conducted at a higher hopper load (568 L). The higher of the two drift measurements was expected to have been associated with the higher load because of increased vortex strength. However, the overall hopper load effect for the test was determined to not be significant ($p<0.05$).

Conclusions

The investigation of the spray drift attributes of a turbine-powered aircraft operating at the high velocities of 218, 241, and 265 km/h yielded the following:

1. Droplet volume median diameter ($D_{V0.5}$) of the spray solution used in the field drift experiment decreased from 247 and 218 μm to 189 μm at the above increasing velocities, respectively. The 241 and 265 km/h

treatment droplet sizes decreased by 11.7 and 23.5%, respectively, from that of the 218 km/h treatment.

2. Field spray drift recovered by air samplers was not significantly different for all velocity treatments at individual sampler stations up to a distance of 67 m from the flightline center. Drift from the 218 km/h treatment was significantly greater than from the higher velocity treatments at distances ranging from 79 to 201 m. Covariants did not significantly ($P<0.05$) account for test variability. A negligible tracer evaporation effect was observed under controlled conditions.

3. The strengths of wingtip aerodynamic vortex of the 241 and 265 km/h treatments, compared to that for 218 km/m, theoretically decreased by approximately 10 and 22%, respectively. The decrease in drift potential from decreasing vortex strength apparently offset the increase in drift potential from decreasing droplet size. The combination of droplet size and vortex strength of the 218 km/h treatment evidently exceeded a critical balance and caused increased spray drift.

4. The FSCBG spray drift model predicted a nearly uniform response in total airborne spray concentration versus distance for all aircraft velocity treatments. The model tended to over-predict concentrations close to the flightline, and under-predict concentrations at distances greater than 100 m when compared to trends in field data.

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Table 1. Mean aircraft and meteorological conditions during each test run. Each run consisted of four aircraft passes.

Run Number	Mean Aircraft Velocity (km/h)	Test Rep.	Initial Hopper Load (L)	Mean Ambient Air Temperature (°C)	Mean Ambient Air Rel. Hum. (%)	Wind Velocity mean (m/s)	Wind Velocity C.V. (%)	Wind Direction mean (°)	Wind Direction C.V. (%)	Stability Ratio (°C s^2/cm^2)
1	218	1	337	27.8	64.5	2.65	18.9	65.4	26.2	0.94
2	241	1	250	28.3	63.1	3.03	19.9	93.2	14.2	-0.72
3	265	1	568	29.1	59.0	2.25	27.6	75.9	28.2	-1.32
4	218	2	481	29.4	57.7	2.74	11.4	69.5	16.2	-0.21
5	241	2	401	30.1	55.6	2.16	29.2	96.3	27.5	1.87
6	265	2	572	30.6	57.2	1.65	47.9	44.3	113.4	0.00
7	241	3	500	30.5	57.4	2.60	25.3	87.8	25.6	-1.06
8	218	3	420	31.1	56.3	2.83	29.6	68.4	26.0	0.04
9	265	3	333	31.1	55.4	3.34	19.9	63.6	20.5	-0.03
10	241	4	261	31.2	56.2	2.57	30.5	46.9	33.4	0.06
11	218	4	182	31.3	55.6	2.69	26.4	63.9	22.7	-0.91
12	265	4	95	30.8	56.3	2.64	16.6	71.0	16.9	-0.63

Table 2. Selected FSCBG spray drift model input variables.

Input Variable	Value
Aircraft Wake Model:	Near Wake
Evaporation Model:	Selected
Concentration Model:	Selected
Aircraft Weight:	3855 kg
Aircraft Wingspan:	13.5 m
Planform Area:	34.09 m^2
Drag Coefficient:	0.1
Propeller Radius:	1.37 m
Propeller Efficiency:	0.8
Propeller Angular Speed:	2000 rpm
Engine Forward Location:	3.66 m
Number of Nozzles:	20
Carrier:	Water
Volatile Fraction of Carrier:	0.9843
Minimum Drop Diameter:	5.0 μm
Emission Rate:	113 L/ha
Swath Width:	15.5 m
Vortex Decay Coefficient:	0.56 m/s
Surface Pressure:	1013 mb
Net Radiation Index:	2.0
Averaging Time:	600 sec
Gaseous Source Depth:	1.0 m

Table 3. Droplet size distributions, $D_{v0.5}$, and relative span of spray mixtures with and without cinnamyl alcohol under simulated aerial application conditions at high air velocities. Spray nozzle was a D6-46 operated at 207 kPa and oriented 45° in the air stream.

Formulation*	Air Velocity (Km/h)	Distribution of Spray Volume in Droplet Diameter Ranges: <72 µm (%)	<125 µm (%)	<204 µm (%)	>310 µm (%)	>442 µm (%)	$D_{v0.5}$ (µm)	Relative Span
W + CA + X-77**	218	0.63	3.53	24.27	17.43	3.00	247	0.75
W + CA + X-77**	241	1.33	7.73	41.33	11.47	2.90	218	0.86
W + CA + X-77**	265	2.87	16.17	59.43	7.93	1.66	189	0.99
W + X-100	218	0.13	0.90	8.17	43.77	8.37	298	0.73
W + X-100	241	0.17	1.57	14.60	27.17	4.13	269	0.69
W + X-100	265	0.40	2.30	21.87	22.67	5.60	253	0.83
W + X-77	241	0.30	1.63	16.80	26.80	4.87	265	0.76
W	241	0.23	1.17	12.03	33.27	6.17	278	0.73

*Symbols represent: W - Water, CA - 1.32% cinnamyl alcohol, X-77 - 0.25% X-77 surfactant, X-100 - 0.1% X-100 surfactant.
**Formulations and test conditions used for drift test.

Table 4. Aircraft velocity effect on cinnamyl alcohol rinsate concentrations removed from air sampler filters.

Aircraft Velocity (km/h)	Mean Rinsate Concentration (ppm)
218	2.46 a*
241	1.22 b
265	1.16 b

*Letters denote least significant difference mean separation ($p < 0.05$) based on analysis using the log transform of concentration. Actual values of concentration are reported.

Table 5. Test replication effect on cinnamyl alcohol rinsate concentrations removed from air sampler filters.

Test Replication	Mean Rinsate Concentration (ppm)
1	0.77 a*
2	1.24 b
3	1.93 c
4	2.91 d

*Letters denote least significant difference mean separation ($p < 0.05$) based on analysis using the log transform of concentration. Actual values of concentration are reported.

Table 6. Effects of aircraft velocity and distance from flightline on mean regression predicted cinnamyl alcohol rinsate concentrations removed from air sampler filters.

Sampler Station	Sampler Distance From Flightline (m)	Regression Predicted Rinsate Concentration* (ppm) Aircraft Velocity (km/h) 218	241	265
1	30	4.33 A**	4.92 A	4.06 A
2	43	3.99 A	4.03 A	3.40 A
3	55	3.68 A	3.31 A	2.84 A
4	67	3.40 A	2.71 A	2.38 A
5	79	3.13 A	2.22 B	1.99 B
6	91	2.89 A	1.82 B	1.66 B
7	104	2.67 A	1.49 B	1.39 B
8	116	2.46 A	1.22 B	1.16 B
9	128	2.27 A	1.00 B	0.97 B
10	140	2.09 A	0.82 B	0.81 B
11	152	1.93 A	0.67 B	0.68 B
12	165	1.78 A	0.55 B	0.57 B
13	177	1.64 A	0.45 B	0.48 B
14	189	1.52 A	0.37 B	0.40 B
15	201	1.40 A	0.30 B	0.33 B

*Predictions were based on log transform of rinsate concentration. Predicted values of concentration are reported.

**Letters denote row-wise mean comparison from SAS Statement "CONTRAST" using log transform of rinsate concentrations. Predicted values of concentration are reported.

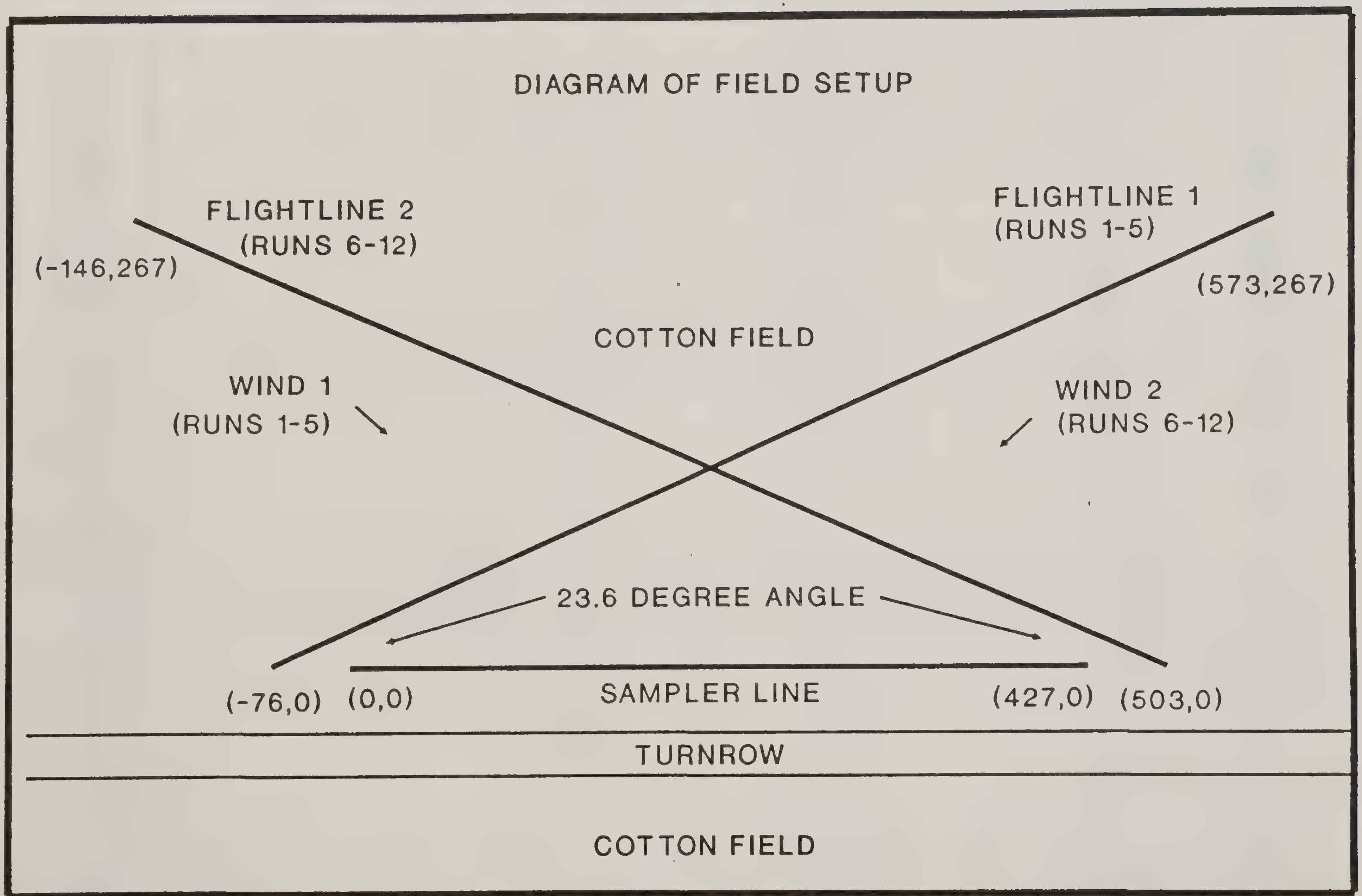

Figure 1. Diagram of field setup used to evaluate drift characteristics of spray applications from a turbine-powered aircraft operating at three velocities. Coordinate dimensions are expressed in units of meter.

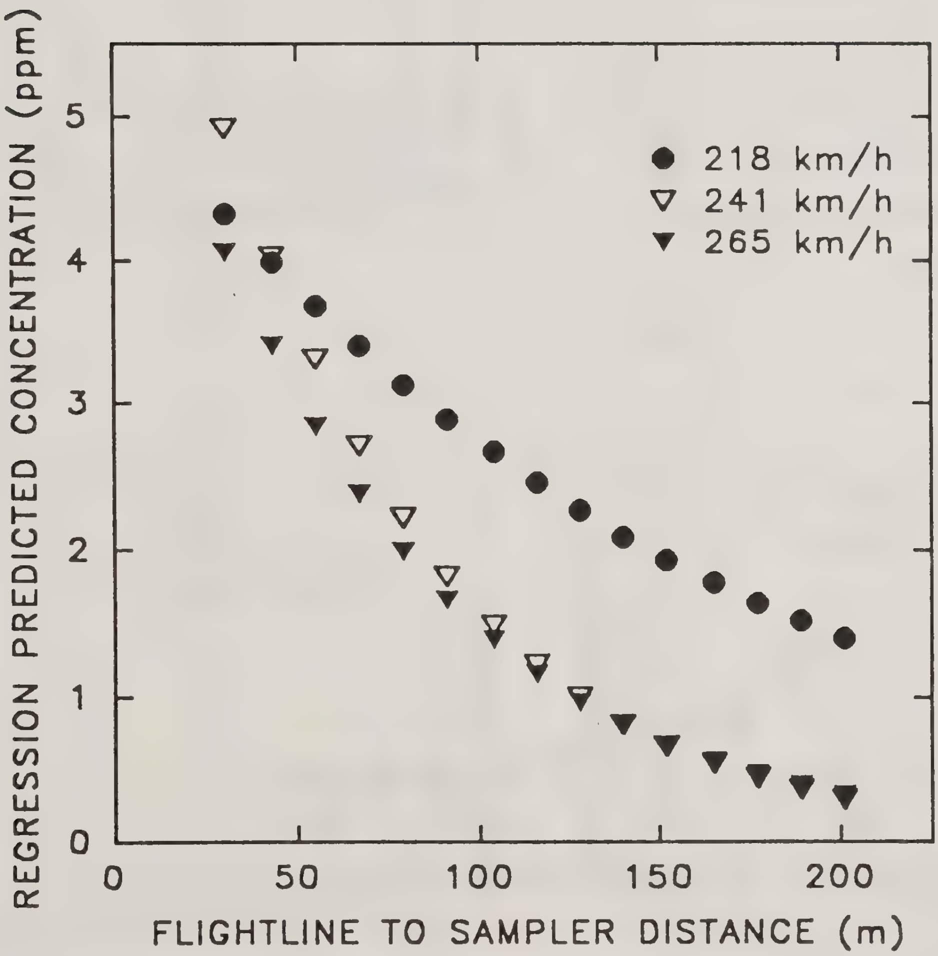

Figure 2. Regression of field data to predict the mean cinnamyl alcohol rinsate concentrations as a function of distance for three aircraft velocity treatments.

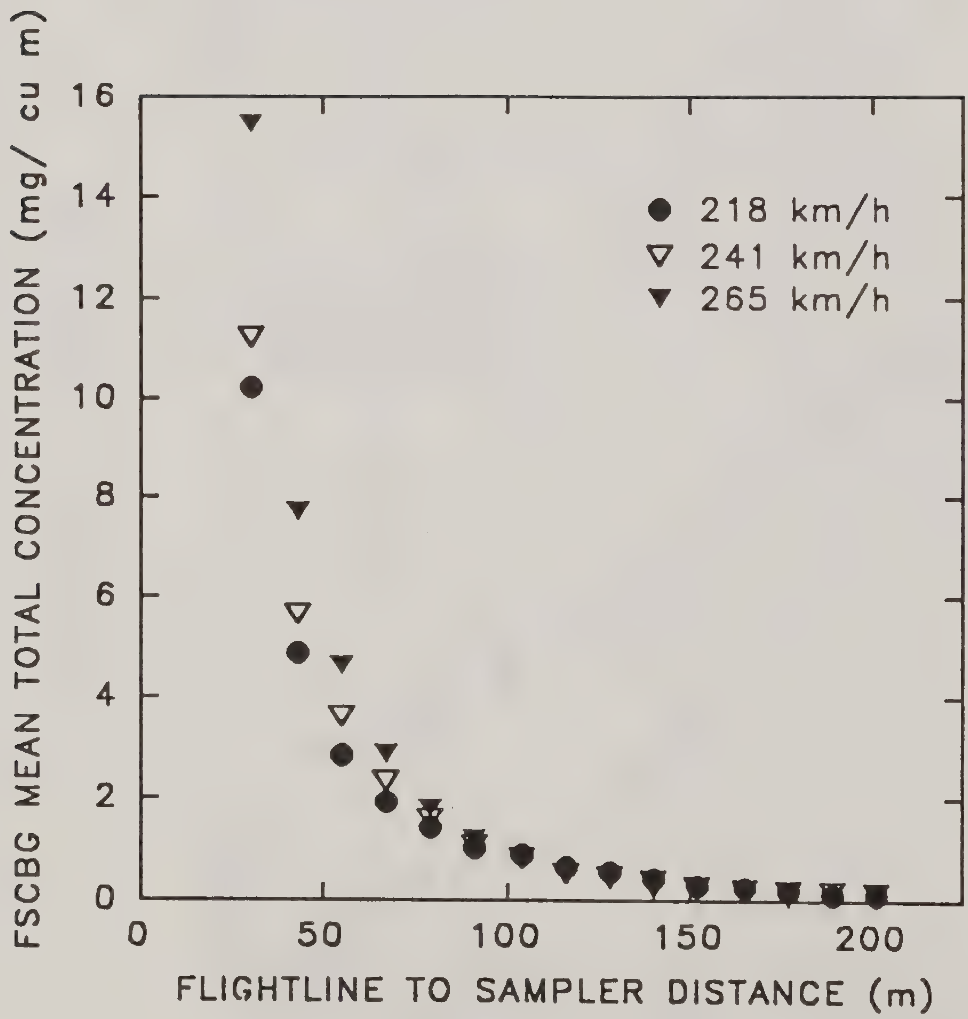

Figure 3. FSCBG spray drift model prediction of mean cinnamyl alcohol airborne concentrations versus distance for the same aircraft velocity treatments and meteorological conditions measured during field tests.

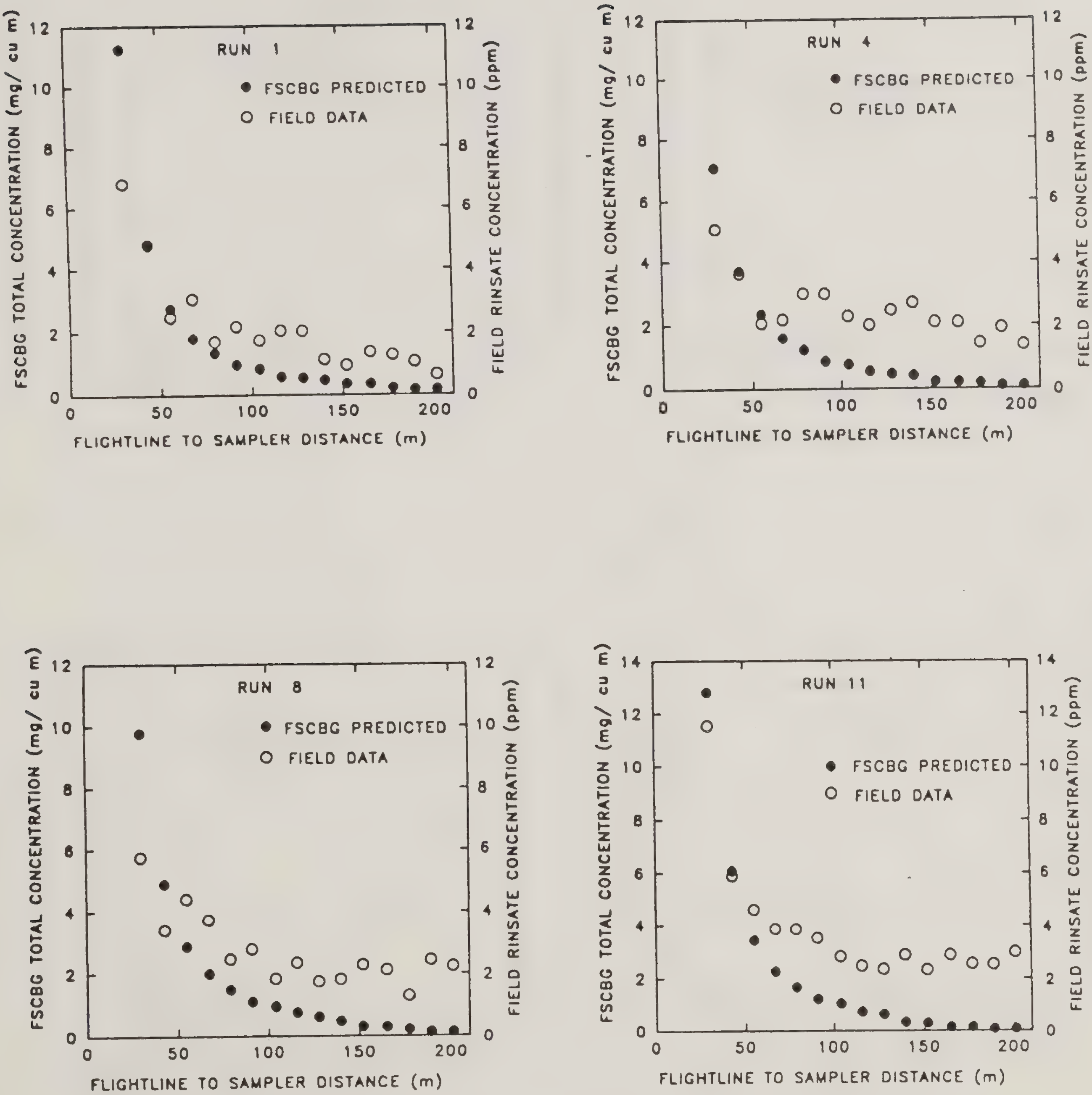

Figure 4. Trend between FSCBG predicted concentration and field air sampler filter rinsate concentration versus distance for the 218 km/h aircraft velocity treatment.

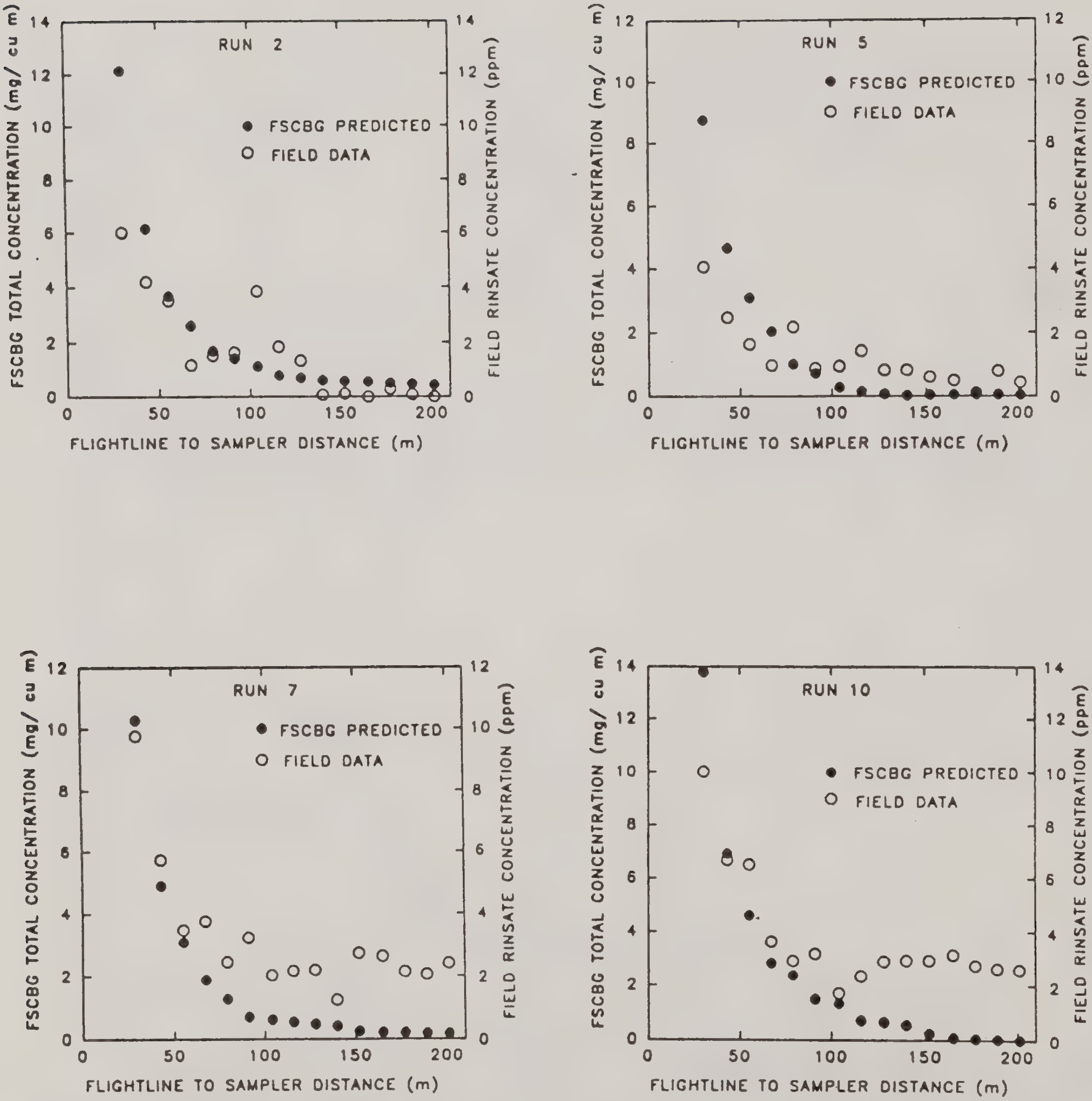

Figure 5. Trend between FSCBG predicted concentration and field air sampler filter rinsate concentration versus distance for the 241 km/h aircraft velocity treatment.

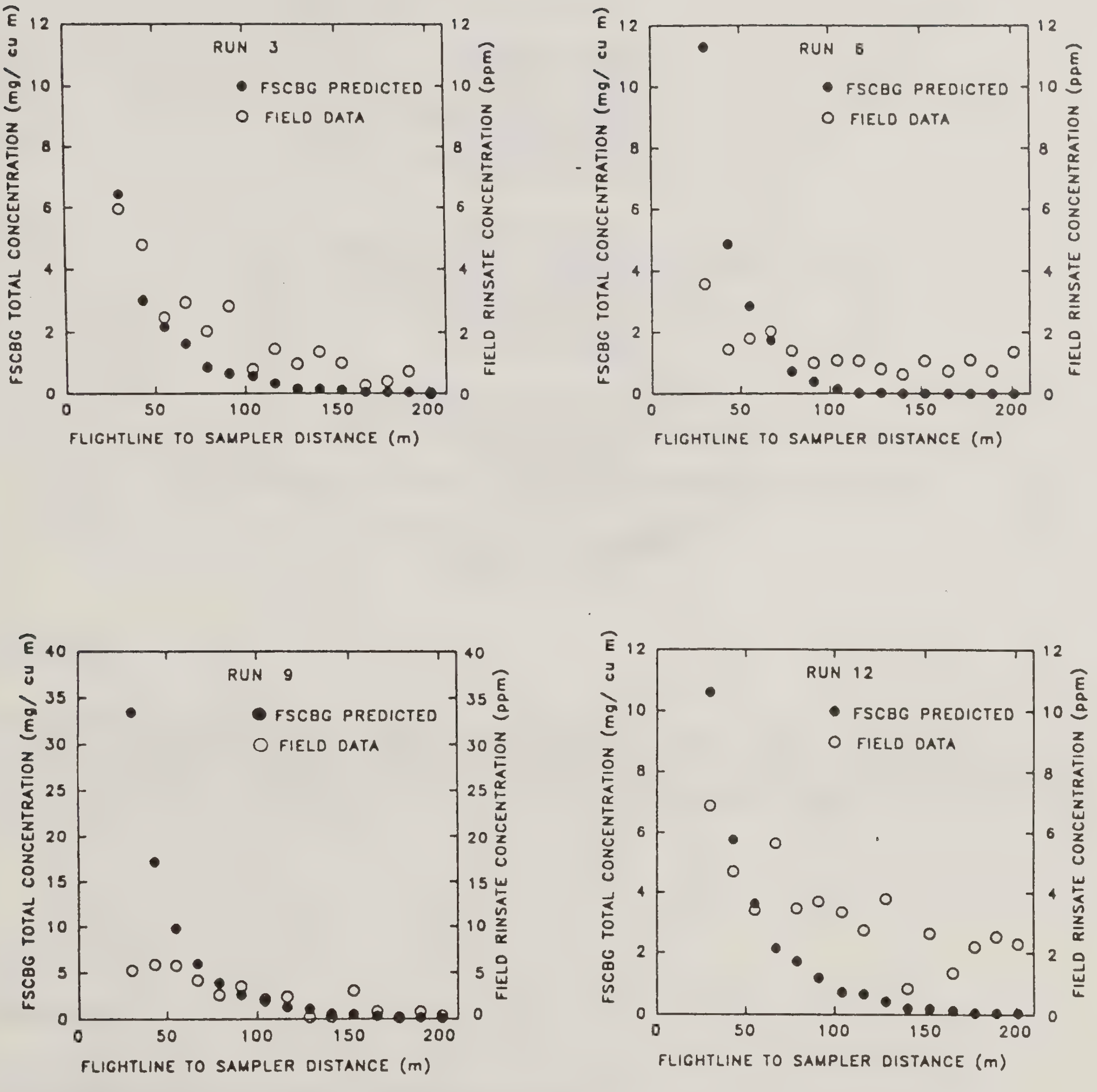

Figure 6. Trend between FSCBG predicted concentration and field air sampler filter rinsate concentration versus distance for the 265 km/h aircraft velocity treatment.

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AN ASAE MEETING PRESENTATION

FSCBG MODEL INPUT SENSITIVITY STUDY

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SUMMARY:

The USDA Forest Service computer product FSCBG Version 4.0 is utilized to develop a sensitivity analysis of all input variables into the model, demonstrating the relative influence of these variables on the deposition and drift patterns of spray material released into the wakes of fixed-wing aircraft and helicopters.

KEYWORDS:

Aerial Sprays, Modeling, Models, Pesticides, Simulation

FSCBG MODEL INPUT SENSITIVITY STUDY

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ABSTRACT

This paper summarizes a complete sensitivity study of all input variables into the FSCBG Version 4.0 computer model, including the near-wake AGDISP representation, helicopter and fixed-wing aircraft, and drop size distribution. A linear analysis is performed around a nominal, or base case, parameter set. Trends in the results may be explained, for the most part, on a physical basis; however, the worth of the present analysis is its quantification of the relative sensitivity of the results to known input variable changes. The importance of these variations are catalogued relative to effectiveness of swath width deposition and off-target drift. These results quantify several critical variables regarding aerial application, specifically those variables that must be carefully controlled or monitored during spray operations.

INTRODUCTION

The USDA Forest Service in cooperation with the U. S. Army has developed the Forest Service Cramer-Barry-Grim (FSCBG) aerial spray model (Teske and Curbishley 1991) incorporating the Agricultural Dispersal (AGDISP) model (Teske 1990). The FSCBG model predicts the transport and behavior of pesticide sprays released from aircraft. The AGDISP near-wake representation solves a Lagrangian set of equations for the position and position variance of material released from each nozzle on the aircraft. The motion of this material is affected principally by the wing or rotor tip vortices, crosswind and evaporation. The FSCBG far-wake representation begins with the results of AGDISP at the top of a defined canopy or near the ground, and solves a Gaussian diffusion equation to recover ground deposition.

The AGDISP model includes simplified models for aircraft wake and ambient turbulence effects including wing-tip vortices, helicopter downwash and forward flight, jet engines and propellers, crosswind, vortex decay and material evaporation. The model tracks the motion of a group of similarly-sized particles or droplets released into the atmosphere from specified nozzle locations. The similarly-sized droplets are combined in a drop-size distribution to generate the spray droplet cloud. The novel feature of the AGDISP model is that the dispersion of the group of similarly-sized droplets resulting from turbulent fluid fluctuations is quantitatively computed within the wake of the aircraft as the group of droplets descends toward the ground. The accuracy with which AGDISP can compute dispersion of this group of droplets is intimately related to specifications of the turbulent fluid fluctuations through which the droplets must pass and the local fluid velocities in the vicinity of the aircraft releasing the material.

FSCBG is a Gaussian line-source model that takes the near-wake results from AGDISP and predicts downwind dispersion including the effects of evaporation, meteorology, canopy penetration, and ground and canopy deposition. FSCBG is a complete-wake model in that it includes an analytic dispersion model for multiple line sources oriented in any direction to the wind, an evaporation model for volatile spray components, a canopy penetration model for forest canopy interception, and the near-wake model AGDISP for initial spray source distribution. A review of the technical aspects of the FSCBG model may be found in Teske 1992 and Teske et al. 1992.

The model is directed toward a complete prediction of the behavior of the spray material after it is released from the nozzles. Drop size distributions give the mass distribution of material as it is atomized by the nozzle. Drops containing volatile materials (such as water) begin to evaporate immediately upon entering the atmosphere, with the local temperature and relative humidity determining the rate of evaporation. The presence of the aircraft wake (with its vortical structure) may move material to unanticipated locations. Ambient winds superimpose additional horizontal velocity vectors on the spray material. Canopy deposition strips spray material and prevents nonvolatile components from reaching the ground. Every aspect of the spray process is affected by the size and significance of atmospheric and aircraft-generated turbulence.

Meteorological calculations generate the background wind speed, temperature and relative humidity profiles. Evaporation calculations track the time rate of decrease of drop size of drops that are released into this background. Canopy calculations remove additional material through impact on vegetation. Near-wake calculations follow the behavior of released spray near the aircraft, and when out of wake influence or at the top of the canopy, hand off to the dispersion calculations to predict the dosage, concentration and deposition at user-designated locations.

Both models have recently been compared against field data (Bilanin et al. 1989 and Teske et al. 1991). The next logical step is to explore the sensitivity of input variables entered into these models. A preliminary sensitivity study appears in Teske, Barry and Ekblad 1991.

At this point many options become available, depending on the aircraft type chosen and the goals of the study. Ideally, two aircraft (fixed-wing and helicopter) would be studied, systematically varying every input parameter and obtaining extensive predicted results that could be appropriately nondimensionalized to collapse the data. To this end the following assumptions have been applied to this study:

1. The USDA Forest Service typically uses the Bell JetRanger helicopter and the Ayres Turbo Thrush fixed-wing aircraft for their gypsy moth spraying. By default these two aircraft become the base case aircraft. To test jet engine and biplane wing sensitivity, the Thrush is modeled with these additional features. Aircraft characteristics are obtained from the FSCBG aircraft library (Hardy 1987).

2. When combating the gypsy moth, the USDA Forest Service typically uses Foray 48B Neat as a spray material. By default this spray material becomes the base case material sprayed in the sensitivity study. Evaporation and downwind drift sensitivity is further explored by spraying water. Drop size distributions are obtained from the FSCBG drop size library (Skyler and Barry 1991) or manipulated from the complete drop size distribution data set.

3. When using the base case aircraft, the USDA Forest Service typically positions four Beecomist rotary nozzles on the Bell JetRanger, and six Micronair rotary

nozzles on the Thrush. These configurations become the base case nozzle types and number, although further sensitivity is explored with 8004 flat fan nozzles to generate a full-boom deposition pattern. Defaults place nozzles across no further than 75 percent of the wing span or rotor diameter.

4. Canopy sensitivity effects are obtained by adding the Heather Seed Orchard canopy characteristics when needed (Teske et al. 1991). The recent FSCBG model additions for the LiCor instrument is not explored.

5. Default meteorological characteristics are assumed typical for spraying in the Northeast for gypsy moth (Teske, Twardus and Ekblad 1990). Advanced options not typically employed by the normal FSCBG user are not explored. Meteorology is assumed with layer-averaged values only.

6. Nonvolatile deposition on the ground will be the predicted result analyzed. Dosage and concentration have not been extensively validated in the model, although these efforts are ongoing (Barry et al. 1992). A single flight line flown perpendicular to a single row of receptors recovers the predicted deposition pattern.

The base case FSCBG input parameter set is given in Table 1. Over 400 FSCBG model calculations were performed for this sensitivity study.

APPROACH

Sensitivity is explored by evaluating the shape and location of the nonvolatile ground deposition pattern referenced to a base case result. Part of the difficulty in such a complex undertaking is that the results will to some extent become a function of the base case conditions chosen. Unfortunately, no convenient way could be found to get around this difficulty; the best that could be done was to develop a consistent base case configuration. This dilemma should not, however, detract from the results of this study and their implications into the accuracy needed for specific inputs to the model.

Sensitivity is computed with linear changes in the base case conditions. Statisticians would probably agree that more sophisticated approaches could be employed, but these methods would perhaps detract from the real intent of this study: namely, generating the importance of input variable accuracy.

In this approach a single variable is changed from its base case conditions, and the effects of this change on deposition profile shape and downwind drift location are evaluated. The two variables of interest are the following:

Figure of Merit. A correlation may be computed for each sensitivity variation and its comparison with the base case, then equated to an algebraic representation:

$$\frac{\mathrm{FOM}}{1 + \mathrm{FOM}^2} = \frac{\int c_b \, c_s \, dy}{\int \left(c_b^2 + c_s^2 \right) dy} \tag{1}$$

where $c_b(y)$ is the appropriate base case nonvolatile deposition pattern; $c_s(y)$ is the sensitivity variation nonvolatile deposition pattern; and y is the horizontal downwind distance (measured relative to the centerline of the aircraft). This definition of Figure of Merit is improved over a previous definition (Teske, Barry and Ekblad 1991) to permit the resulting calculations to be more directionally independent, and to reflect the true change between the two deposition patterns. Whether c_b or c_s is the base case condition, the same value of FOM will be computed when employing Equation 1 to interpret FSCBG results, along with the restriction that $FOM < 1$.

If the sensitivity variation gives exactly the same deposition pattern as the base case, the Figure of Merit will equal unity. If c_s is always one-half of c_b everywhere, or twice c_b everywhere, FOM then equals 0.5 . Thus it may be seen that FOM reflects the percentage difference in the nonvolatile deposition pattern from the two deposition patterns. If an acceptable criterion is a ten percent variation in pattern shape, then FOM may reasonably vary from 0.9 to 1.0 in the sensitivity.

Mean Horizontal Position. The nonvolatile ground deposition pattern may be examined to recover the volume-averaged mean horizontal position, measured downwind relative to the aircraft centerline. Nondimensionalization is achieved by dividing the result by the mean horizontal position of the base case to recover the Mean Horizontal Position MHP. This variable then gives an indication of the drift of the material with the sensitivity. If an acceptable criterion is a ten percent variation in mean deposition location, then MHP may reasonably vary from 0.9 to 1.1 in the sensitivity.

Comparing variable sensitivities among themselves requires formulating a convenient nondimensional number. If a base case variable (from Table 1) is designated V_b , and the sensitivity examines the variable with a value of V_s , it seems clear that the Figure of Merit leads to a nondimensional number of the form:

$$\text{FOM Factor} = \frac{\text{FOM} - 1}{V_s / V_b - 1} \tag{2}$$

It may be seen from Equation 2 that when a ten percent increase in V_b to V_s recovers a FOM = 0.9 , the FOM Factor = 1.0 . This factor will then directly interpret all sensitivities in the present study.

The Mean Horizontal Position may be interpreted similarly to give:

$$\text{Drift Factor} = \frac{\text{MHP} - 1}{V_s / V_b - 1} \tag{3}$$

It may be seen from Equation 3 that when a ten percent increase in V_b to V_s recovers a MHP = 1.1 , the Drift Factor = 1.0 . This factor will then also directly interpret all sensitivities in the present study.

SENSITIVITY RESULTS

The principal results of this study are the ordering of sensitivities displayed in Table 2. All controllable inputs into FSCBG were examined by running the Bell JetRanger and the Ayres Turbo Thrush with both the appropriate rotary atomizers, and with nineteen 8004 flat fan nozzles positioned across 75 percent of the rotor diameter or wing span. Each variable sensitivity involved increasing the variable input above the base case value displayed in Table 1, and decreasing the variable input below the same base case value. The (typically) eight FOM Factors computed (Beecomists on the JetRanger, Micronairs on the Thrush; 8004s on both aircraft; with plus and minus differences) were then averaged to produce the Average FOM Factors displayed in Table 2. The (typically) eight Drift Factors were treated similarly. Both of these numbers were averaged to yield the Average Overall Factors with which the table ranking was established.

The worth of Table 2 is that, even though these numbers suggest the accuracy of all FSCBG model predictions based on each input variable, these numbers may also be used to infer the accuracy needed to collect data in an actual spray mission.

The numbers in Table 2 may be interpreted most clearly by example. If the wing span of the aircraft is known, for instance, to within only 10 percent of its actual value (an unlikely event), the deposition pattern will be predicted by FSCBG to within only 31.85 percent of what FSCBG would predict if the wing span were entered correctly (10 times 3.185 from the first column of numbers in Table 2). This scale-up effect is why the value of wing span is the most important entry into FSCBG.

Typically, every entry into the model should result in no worse than a 1 percent effect on the deposition profile (mutual effects from several input errors have not been explored, and probably never will because of its extreme complexity). This criterion would suggest that the wing span should be known to within 0.3 percent of its actual value (1 divided by 3.185). Since the wing span can be measured precisely, this level of accuracy should not be a problem here.

However, other variables in Table 2 may not be so lucky. Release height, specific gravity, wind speed, actual nozzle drop size distribution (reflected in this case through its volume median diameter VMD), pressure, aircraft spraying speed and wind direction all require careful meteorological field measurements, or laboratory and wind tunnel studies, to support a 1 percent confidence in the inputs entered into FSCBG, and influencing the deposition in any actual spray mission. Wind speed and direction are particularly tricky here because these parameters are usually evaluated by averaging over a 10-minute data collection time interval. The relative standard deviations from their average values essentially become a measure of the accuracy of these variables.

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Table 1. Base Case Sensitivity Parameter Set

Aircraft Characteristics		
Aircraft Type	Bell JetRanger	Ayres Turbo Thrush
Weight (kg)	989.3	2745.5
Rotor Diameter / Wing Span (m)	10.17	13.54
Planform Area (sq m)		28.16
Drag Coefficient		0.1
Propeller Radius (m)		1.296
Propeller Efficiency		0.8
Blade RPM	384.0	2000.0
Spray Characteristics		
Spray Material	Foray 48B Neat	Foray 48B Neat
Specific Gravity	1.0	1.0
Volatile Fraction	0.15	0.15
Spraying Speed (mph)	60.0	110.0
Relative Height (ft)	50.0	50.0
Nozzle Type	Beecomist (4)	Micronair (6)
Emission Rate (gal/min)	5.0	5.0
Meteorological Conditions		
Vortex Decay Coefficient (m/s)	0.56	0.56
Pressure (mb)	1013.0	1013.0
Net Radiation Index	1.0	1.0
Temperature (deg F)	60.0	60.0
Relative Humidity (percent)	65.0	65.0
Crosswind Speed (mph)	3.0	3.0
Canopy Characteristics		
Canopy Height (m)	15.0	15.0
Stand Density (stems/acre)	25.0	25.0
Penetration Probability	0.38	0.38
Vegetative Element Size (cm)	3.0	3.0
Other Characteristics		
Jet Thrust (kg)		3264.0
Jet Radius (m)		1.296
Biplane Wing Separation (m)		1.0

Table 2. Sensitivity Factors Generated by FSCBG Predictions

Variable	Average FOM Factor	Average Drift Factor	Average Overall Factor
Wing Span	3.185	1.033	2.109
Release Height	1.981	1.892	1.936
Specific Gravity	2.125	0.805	1.465
Nozzles Horizontal	2.429	0.371	1.400
Rotor Diameter	1.456	0.961	1.209
Wind Speed	1.166	0.981	1.073
VMD	0.771	1.154	0.963
Surface Pressure	1.492	0.412	0.952
Spraying Speed	1.504	0.388	0.946
Canopy Height	1.562	0.152	0.857
Wind Direction	0.750	0.765	0.757
Aircraft Weight	0.672	0.254	0.463
Vortex Decay Coefficient	0.456	0.221	0.338
Helicopter Blade RPM	0.382	0.275	0.329
Tree Envelope Width	0.548	0.053	0.301
Nozzles Vertical	0.402	0.201	0.301
Propeller Efficiency	0.460	0.099	0.279
Temperature	0.331	0.079	0.205
Tree Density	0.356	0.048	0.202
Biplane Wing Separation	0.341	0.060	0.200
Penetration Probability	0.353	0.032	0.193
Propeller Blade RPM	0.318	0.066	0.192
Net Radiation Index	0.298	0.085	0.191
Propeller Radius	0.283	0.078	0.180
Drag Coefficient	0.277	0.057	0.167
Planform Area	0.277	0.057	0.167
Evaporation	0.243	0.085	0.164
Volatile Fraction	0.269	0.056	0.163
Engine Vertical	0.202	0.053	0.127
Engine Forward	0.180	0.011	0.096
Jet Thrust	0.146	0.030	0.088
Relative Humidity	0.141	0.022	0.082
Number of Drop Sizes	0.110	0.036	0.073
Nozzles Forward	0.103	0.044	0.073
Number of Nozzles	0.107	0.016	0.061
Leaf Element Size	0.057	0.025	0.041
Jet Radius	0.047	0.023	0.035

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PREDICTING SPRAY DRIFT IN COMPLEX TERRAIN

by

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SUMMARY:

A study was conducted in complex terrain of Parley's Canyon, Utah during June 1991 to compare off-site movement of a biopesticide formulation of *Bacillus thuringiensis* (Bt) to FSCBG aerial spray model predictions. Other study objectives were to quantitate the amount of Bt that moved off-site under drainage winds and to compare different methods of sampling spray movement. The site was treated three times under similar atmospheric conditions. Positive recoveries of Bt were detected downwind to 3,150 meters. The paper presents comparisons of sample types and model predictions to field data, and provides recommendations for follow-up studies.

KEYWORDS:

Aerial sprays, Modeling, Drift, Agricultural Pesticides, Forests

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PART 1
FSCBG AERIAL SPRAY MODELS

Introduction

For the last 20 years the U.S. Department of Agriculture Forest Service (Forest Service) and the U.S. Army have been partners in pursuing the development of computer models that predict the deposition and dispersion of aerially released material. As a steward of vast natural resources, the Forest Service has need for aerial application capabilities to manage forest pests that oppose resource management objectives. This need for safe, economical, and effective application of spray material has dictated the construct of computer models to simulate and study the behavior of spray material released into the atmosphere. The models are used to predict the environmental fate of aerially released pesticides with accountability from the moment of atomization to their ultimate deposition on surfaces. The two models discussed in this paper represent mechanisms of the environmental accountability process that can hand-off predictions to ground and water fate models for total environmental fate predictions.

The Forest Service Cramer-Barry-Grim (FSCBG) model (Teske et al. 1992a) is a Gaussian line-source model that takes the near-wake results of AGricultural DISPersal (AGDISP) model (Bilanin et al. 1989) and predicts downwind dispersion including the effects of evaporation, meteorology, canopy penetration, and ground and canopy deposition.

Simplified aerial line source models were originally developed by the U.S. Army in the early 1960's (Cramer et al. 1972). These models were first applied to forestry use in determining optimum swath widths and application rates in testing of insecticides under consideration at that time for insect control applications in western forests (Barry et al. 1974; Waldron 1975; and Barry and Ekblad 1983). The implications of these early efforts in the use of mathematical models to improve the planning, conducting and subsequent analyzing of spray program operations and results were noted by Dumbauld, Cramer and Barry (1975) and led to field evaluation (Boyle et al. 1975) and the development of the FSCBG model (Dumbauld, Rafferty, and Bjorklund 1977a). Further work used the model to determine offset distances in environmentally sensitive areas of Maine (Dumbauld and Bjorklund 1977b). Various aircraft were modeled to evaluate drift from spray blocks to determine potential determinable environmental hazard to exclusion areas (waterways, homes, etc.) in the vicinity of the spray blocks.

Continued success in simulating field experiments and control operations lead to the development of FSCBG (Dumbauld, Bjorklund, and Saterlie 1980a). FSCBG was subsequently applied to the development of optimum swath widths, application rates, and aircraft release heights in other projects (Dumbauld, Bowman, and Rafferty 1980b) and a pilot project in the Withlacoochee State Seed Orchard (Rafferty et al. 1981) that led to wide acceptance of aerial application in forestry seed orchards of the Southeast. Further refinements to the model included the addition of the near-wake model AGDISP (Bjorklund,

Bowman, and Dodd 1988) and most recently enhanced and a rewrite of the FSCBG user interface by Teske and Curbishley (1991).

FSCBG Description

FSCBG takes input data entry from meteorological conditions, aircraft details (through AGDISP inputs), nozzle specifications, spray material information, canopy characteristics, and flight path scenario.

(1) Meteorological conditions anticipated during the spray mission (such as ambient temperature, relative humidity, wind speed and direction, and turbulence);

(2) Aircraft information (including weight, wing span, flight speed, spray release height);

(3) Nozzle information (number of nozzles, type of nozzle, locations on boom, flow rate of material through nozzles);

(4) Spray material information (specific gravity, drop-size distribution, volatile fraction);

(5) Canopy information (height of canopy, general shape, stand density: stems per acre); and

(6) Mission scenario (number of aircraft passes, lane separation, length of these passes, flight direction).

Two data bases have been constructed to aid in the selection of inputs to FSCBG. An aircraft description data base contains the pertinent characteristics from 109 aircraft used by the Forest Service and its aerial application contractors (Hardy 1987). A drop-size distribution data base contains 243 drop-size distributions from various nozzle types, flow rates, spray material, etc. (Skyler and Barry 1991). This information flows into a series of calculations involving the selected or input data for meteorology, evaporation, canopy penetration, near-wake (AGDISP) and dispersion.

FSCBG predicts the behavior of the released spray material near the wake of the aircraft (with the AGDISP model) and into the far wake. The model is directed toward a prediction of the behavior of the spray material after it is released from the nozzles. Drop size distributions give the mass distribution of material as it is atomized by the nozzle. Drops containing volatile materials (such as water) begin to evaporate immediately upon entering the atmosphere, with the local temperature and relative humidity determining the rate of evaporation. The presence of the aircraft wake (with its vortical structure) may move material to unanticipated locations. Ambient winds superimpose additional horizontal velocity vectors on the spray material. Canopy deposition strips spray material and prevents nonvolatile components from reaching the ground. Every aspect of the spray process is affected by the size and significance of atmospheric and aircraft-generated turbulence. Chemical reactions and terrain effects are, however, excluded.

Meteorology calculations generate the background wind speed, temperature and relative humidity profiles. Evaporation calculations track time rate of decrease of drops released into this background. Canopy calculations remove additional material through impact on vegetation. Near-wake calculations follow the behavior of released spray near the aircraft, and when out of wake influence or at the top of the canopy, hand off to the dispersion calculations to predict the dosage, concentration and deposition at user-designated location. Each calculation module uses data previously developed to continue the solution process.

Model Evaluation

Field evaluations have played a critical role in the development of the model. Many improvements were in fact made possible by the qualitative agreement of model predictions with field data. The model simulates many of the complex processes occurring behind an aircraft and in the atmospheric boundary layer with accuracy and simplicity, but to do so it requires a careful set of measurements before quantitative comparisons can be made. As the usefulness of the model has improved, so too has the knowledge of which variables are more important and must be measured accurately. Early field tests were not designed for model evaluation and thus suffered from too little data to make accurate comparisons with FSCBG predictions; more recent field studies have included the data needed to predict aerial applications with confidence. Six field evaluations (Table 1), conducted in a range of settings from flat open terrain to forested mountain canyons, have provided data to develop and compare FSCBG predictions. All evaluations measured deposition with the exception of Utah 1991 that, in addition to deposition, also measured air concentration, dosage and flux downwind of the treatment area. Results of these evaluations and comparison of observed data to FSCBG model predictions are provided in the references listed in the table. Results show good agreement between predictions and observations with predictions ranging from 8 to 200 percent of the observed data. We believe these are remarkable predictions given the range of test site diversities, complexities of meteorology, limitations of sampling, and challenges of field testing. The most recent field evaluation (Utah 1991 Table 1) has been selected for discussion in Part 2 - "Complex Terrain Drift Study" contained in this paper. Other studies (Anderson et al. 1991) are in progress to evaluate FSCBG prediction of deposition in deciduous canopies.

Table 1. Summary of some field studies used to evaluate FSCBG.

	Montana	Dugway Utah	Withlacoochee Florida	Red Bluff California	Heather Oregon	Utah
Year	1974	1974	1980	1986	1989	1991
Aircraft	Bell 47G3B2	DC-7B	Stearman Hughes 500C	C-130 Bell 205	Bell 47G3B2	Bell 206
Nozzle Types	80015	---	D6-46 D2-45	8020 D4-45	D4-45	Beecomist
VMD (um)	200	50 - 68 350	350 330	175 264	>350	240
Site	Coniferous forest	Open desert	Pine seed orchard	Mountain/ forest	Douglas-fir seed orchard	Mountain/ forest
Measurements	Deposition	Deposition	Deposition	Deposition	Deposition	Deposition Air concentration Total flux
References	Dumbauld, Rafferty, and Bjorklund (1977b)	Boyle, et al. (1975)	Rafferty, et al. (1981)	Rafferty and Bowers (1989) and Rafferty and Bowers (1992)	Teske, et al. (1991a)	Barry, et al. (1992)

FSCBG Model Status

Membership in the FSCBG user group is represented by Federal and State agencies, universities, and the private sector. Model users include researchers, hazard assessment consulting firms, and organizations engaged in aerial application. The FSCBG User Group, administered by Continuum Dynamics, Inc., P.O. Box 3073, Princeton, New Jersey, 08543, (609) 734-9282 under a Memorandum of Understanding with the Forest Service, sponsors training, provides model operating code and updates, and user manual. The National Spray Model Advisory Committee, made up of scientists with interest in the model, meets annually to recommend development and evaluation activities and to coordinate their respective needs.

PART 2
COMPLEX TERRAIN DRIFT STUDY

Introduction

Drift of chemical insecticides and other non-biological simulants in western mountains from aerial application has been investigated by a limited number of researchers. These include: Yates and Akesson (1978) and Ghasseml et al. (1982) reported drift of a chemical insecticide drift over several thousand meters from forest spray projects in Montana and New Mexico; Barry et al. (1983a) reviewed near-field drift from spraying of coniferous seed orchards; Dumbauld, Rafferty, and Bjorklund (1977) and Dumbauld (1981) analyzed drift from an insecticide simulant in a mixed coniferous stand in Montana; Barry and Ekblad (1983b) reviewed spray drift modeling by the Forest Service; Markin (1982) reported on study of chemical insecticides in the State of Washington observing drift 2386 meters downwind; and Rafferty and Bowers (1990) reported drift of an insecticide simulant from a study in the mountains of northern California. Murray and Vaughn (1970) used the Rotorod sampler to monitor drift to four miles in an insect vector study. None of these studies involved biopesticides, thus leaving a data void for the Forest Service whose constituency is expressing environmental concerns over the drift of biopesticides (Sassaman 1987).

Objectives

Task 1 - to evaluate the Wagner, Rotorod, and Mylar sheet samplers for detecting and measuring air concentration, dosage, impaction, and deposition resulting from off-site movement of a biopesticide spray in complex terrain.

Task 2 - to quantitate, subject to success of Task 1, off-site movement of a biopesticide as measured from air drawn, impaction, and deposition samplers.

Task 3 - to compare FSCBG model predictions of dosage and deposition to observed data obtained from field samplers.

Methods

This 1991 study was conducted by the Forest Service in cooperation with the U.S. Army and the State of Utah in Utah's Wasatch Mountains in conjunction with an operational control project to control *Lymantria dispar* L. (gypsy moth) in *Quercus gambelli* Nutt. (Gambel oak) along the canyons of the Wasatch Range. The operational project provided an economic and logistical backdrop that made this study practical and feasible. There were no additional costs for aircraft, biopesticides, and administrative services.

The selected study site was located in Parley's Canyon along Interstate 80 between Salt Lake City, Utah and Summit Park, Utah. The elevation of the treatment block ranged from 1721 to 2126 meters MSL with samples located down canyon at elevations from 1721 descending to 1568 meters MSL (Figure 1). Under high pressure atmospheric conditions and clear skies down-canyon drainage winds are established after sunset continuing for approximately 2-3 hours after

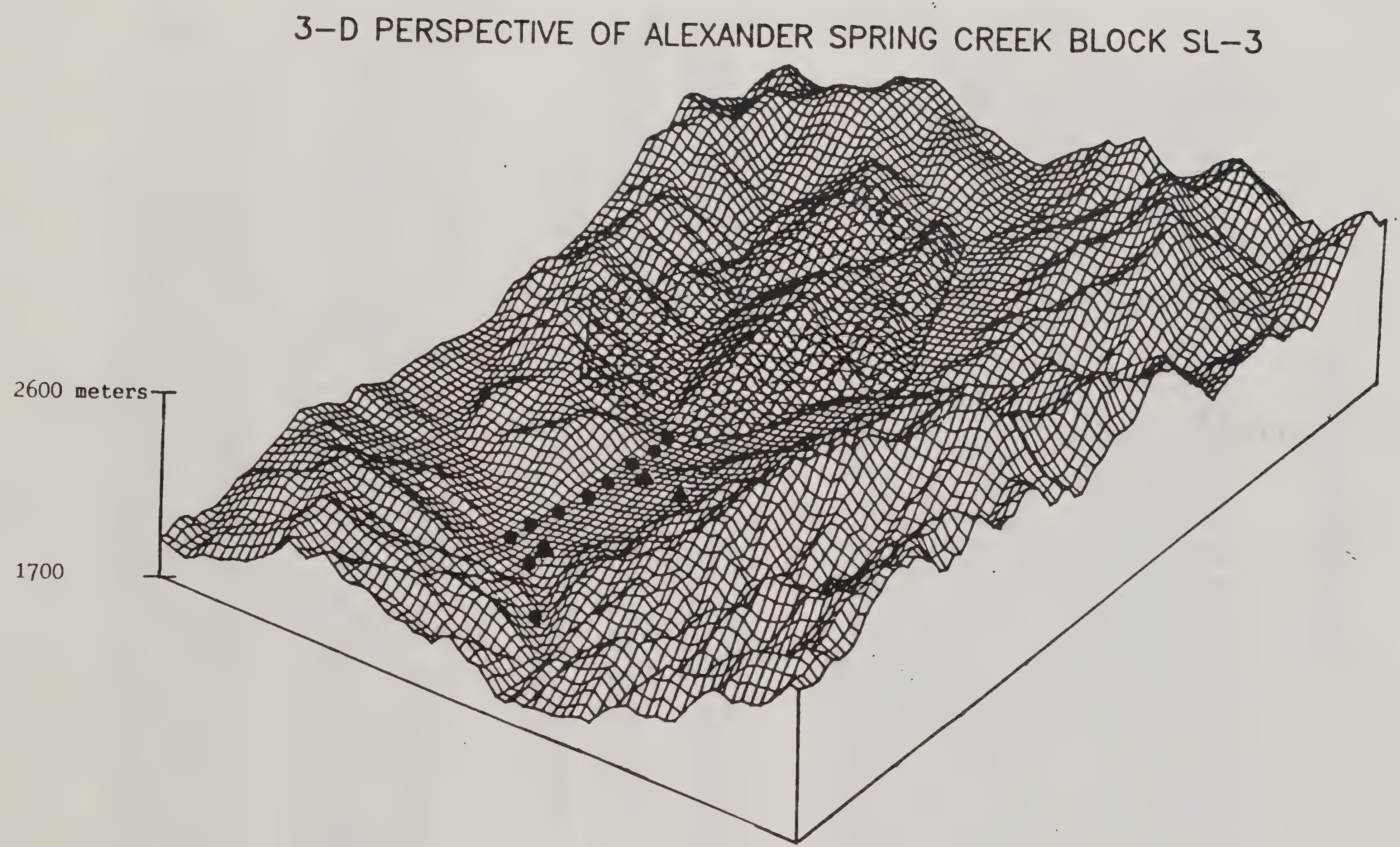


Figure 1. Perspective of study area with ● representing downwind sampling locations and ▲ representing meteorological stations. Treatment area (shaded) 834 hectares.

sunrise. The topography, weather, and logistics provided a favorable opportunity to conduct an off-site movement study to address the objectives stated herein.

The operational treatment involved application of a biopesticide applied by Bell 206 helicopter at 4.68 liters per hectare to a 842 hectare (2080 acre) block (Figure 1). The treatments, to be referred to as trials or applications in this report, were repeated three times at 5-6 day intervals thus providing a replicated study of three trials. Spray application parameters are summarized in Table 2 and 3.

Weather was monitored by three EMCOT meteorological stations (Ekblad, Windell and Thompson 1990). The 6-meter EMCOT masts (Figure 1) were instrumented at two levels to measure wind at 1-second intervals along with temperature and relative humidity.

Spray that moved off the treatment site was measured from the edge of the block at 10 locations down-canyon to 3150 meters to obtain quantitative data on air concentration, total flux dosage, and deposition. Duplicate sampling stations, located at each of the 10 locations, (for a total of 20 stations) consisted of a pair of spinning Rotorods (for dosage) (Edmonds 1972), a pair of non-spinning Rotorods (for total flux), a pair of Mylar sheets (for deposition), and a set of Wagner filter samplers (for dosage) (Wolf et al. 1959). The Wagner filter samplers were not paired but a total of 4 at each station were sequenced during the sampling period with the aggregate recoveries yielding a total sample of dosage for each trial. Therefore, at each downwind sampling location there were four of each sampler type and two sets of the Wagner samplers. All samplers were activated before spray cloud arrival and deactivated when we calculated that the cloud had passed each sampling location. Special precautions were taken to preclude sampler contamination.

The biopesticide spray material was a commercial formulation of <u>Bacillus thuringiensis</u> Berliner var. <u>kurstaki</u> (Bt), a bacterium produced by Novo Nordisk Co. called Foray 48B[R]. Bt produces both an endotoxin and an endospore. For most insects that are susceptible to Bt (those with an alkaline gut) both the endotoxin and endospore have a role in producing infection, (Harper 1974). Bt is an ideal biological organism for use as a tracer in drift studies as the endospore is relatively hardy and persistent, and easy to assay in the laboratory. The Forest Service uses Bt to control forest insects to include gypsy moth, western spruce budworm, and Douglas-fir tussock moth, thus providing opportunities for biopesticide fate studies.

<u>FSCBG Solution Technique</u>

Information and data needed to make the FSCBG model runs were obtained at the study site and from references (Tables 2 and 3). The approach was first to analyze the meteorological data collected by the 3 EMCOT weather stations (Ekblad 1990). One second wind averages were examined by developing ten minute averages of the speed and direction using the METDAT program (Teske 1991). This procedure extracted the azimuthal and elevational standard deviations, and recovered the average temperature, relative humidity, wind speed and wind direction for entry into FSCBG. The drop size spectrum from wind tunnel atomization studies reported by Skyler and Barry (1991) was modified to provide more detailed sub-categories in the driftable part of the spectrum (Table 3).

Practicalities of modeling each flight line swath over the entire 834 hectares (2,060 acres) treatment block necessitated preparing a sub-routine that combined flight lines resulting in the same spray source application and geometry.

Table 2. Application parameters and general input to FSCBG model.

Meteorology	TRIAL 1	TRIAL 2	TRIAL 3
Wind Speed (meters/second)	1.14	1.34	1.34
Temperature (degrees C)	12.74	12.20	9.87
Relative humidity (percent)	66.75	50.12	51.95

Application	
Aircraft	Bell Jet Ranger III
Speed	113 kilometers/hour
Release height	22.85 meters
Atomizer	4 each Beecomist 360A
Application rate	4.68 liters/hectare
Swath width	30.5 meters

Spray Material	
Tank mix	*Bacillus thuringiensis* biopesticide Novo Foray 48B undiluted
Source strength	7.3×10^9 spores or colony forming units per milliliter
Specific gravity	1.16
Volatile fraction	0.15
Atomization	(See Table 3)
Canopy	FSCBG canopy routine not invoked

Table 3. Droplet spectrum for spray material (Foray 48B undiluted) used as input to FSCBG model.

AVG DIAMETER	MASS FRACTION
16.45	.0002
28.72	.0005
43.00	.0016
59.54	.0047
78.65	.0126
100.73	.0297
126.20	.0604
155.62	.1046
189.57	.1545
228.75	.1888
273.97	.1852
326.17	.1394
386.40	.0784
455.93	.0302
536.16	.0077
628.76	.0014

NUMBER MEAN DIA. = D_{10}.... 109.64 um
VOLUME MEAN DIA. = D_{30}.... 156.20 um
SAUTER MEAN DIA. = D_{32}.... 212.92 um

NUMBER MEDIAN DIA. = $D_{N.1}$.... <56 um; $D_{N.5}$.... 88.37 um; $D_{N.9}$.... 217.66 um

Relative Span = 1.09

VOLUME MEDIAN DIA. = $D_{V.1}$.... 140.05 um; $D_{V.5}$.... 240.76 um; $D_{V.9}$.... 403.68 um

Note: The droplet spectrum is a recombination of the droplet spectrum from page 10 of Skyler and Barry (1991).

Spray that moved off the treatment site was measured from the edge of the block at 10 locations down-canyon to 3150 meters to obtain quantitative data on air concentration, dosage and deposition. There were duplicate sampling stations, located at each of the 10 downwind distances, for a total of 20 stations. Each station consisted of a pair of spinning Rotorods, a pair of non-spinning Rotorods, a pair of Mylar sheets, and a set of Wagner filter samplers. The Wagners were not paired but a total of 4 at each station were sequenced during the sampling period with the aggregate recoveries yielding a total sample of dosage for each trial. Therefore, at each downwind sampling distance there were four of each sampler type and two sets of the Wagner samplers. All samplers were activated before spray cloud arrival and deactivated when we calculated that the cloud had passed each sampling location.

Sampler duplication, both in numbers and types, was considered critical to this study. When evaluating a physical model that precisely predicts by the laws of physics and the atmosphere, one must take great care in the selection and use of samplers and sampling techniques used to collect data from model evaluation. Potential errors from the sampling processes are many and include: field and laboratory contamination; motor, pump, or battery failure; sampling schedule errors; assay failures; and incorrect sample labeling. For these reasons it is prudent to increase sampler density, provide duplicates, and use more than one type of sampler. We believe from a statistical viewpoint fewer stations with a high sampler density is superior to more stations with low sampler density.

The brass "U" shaped Rotorod described by Edmonds (1972) samples the air at a rate of 120 liters per minute and is considered 100 percent efficient for the particles sizes in this study. Non-spinning Rotorods were also positioned in pairs at each sampling station to measure, by impaction, the total flux (total amount of spray that passed by the Rotorod). Rotorods were washed in the laboratory and the effluent diluted following procedures described in an appendix of Barry (1992) and plated on agar plates to yield colony forming units (CFU). The rotating Rotorods yielded dosage data in CFU minutes per liter of air and the non-spinning Rotorods yielded total impaction in CFU.

The Wagner samplers contained a calcium alginate fiber that was rated at 99.9 percent efficient for particles > 0.3 um. They sampled air at the rate of 12.5 liters per minute and are considered 100 percent efficient compared to the all-glass impinger (Wolf et al. 1959). The Wagners were sequenced to preclude over dosing the filter over the long sampling period. Assay of the Wagners involved dissolving the filter, diluting the effluent, and plating on agar as with the Rotorod samples. Wagners yield dosage data expressed as CFU minutes per liter of air.

Mylar sheets were placed in pairs at each station downwind to 1550 meters to measure fallout deposition. These too were assayed by washing and plating yielding CFU per square centimeters.

Results

Results of the three tasks - sampler performance, drift quantification, and FSCBG predictions are summarized in this section.

Results of Sampler Performance (Task 1)

To evaluate the consistency in sampler performance for each of the three trials we calculated the standard deviation (Table 4) of the measurements by the four sampler types. The standard deviation measures the variation of duplicated paired samplers located at each of the 10 paired stations along the downwind sampling line. The equation used to compute its relative standard deviation RSD of the dosage, impaction and deposition levels D_i was:

$$RSD = \frac{1}{\overline{D}}\left[\frac{1}{N}\sum(D_i - \overline{D})^2\right]^{1/2}$$

where

$$\overline{D} = \text{average value} = \frac{1}{N}\sum D_i$$

the index i denotes each dosage, impaction and deposition data entry and N denotes the total number of data points considered. A set of data well-approximated by its average value at each downwind distance might have a relative standard deviation as high as 0.1. A level of 0.1 would imply that the data exhibits a standard deviation of 10 percent from the average value at each downwind distance. The combined column of the table gives standard deviation when the three trials are treated as a single trial. These results show consistency from trial to trial, but indicate some variation between the instruments at each downwind distance. The spinning Rotorods exhibit the least amount of variation, and the non-spinning Rotorods, the most. Most of the samplers demonstrate excellent correlation with others at the same downwind location, but one or two locations account for most of the deviation in data collection. For example, the 900-meter Mylar samplers in Trial 1 demonstrated significantly greater differences than at other locations during that particular trial.

Table 4. Relative standard deviations at paired duplicate sampling stations for each type sampler.

Sampler	Trial 1	Trial 2	Trial 3	Combined
Spinning Rotorods	0.143	0.174	0.196	0.172
Wagner Samplers	0.236	0.312	0.319	0.291
Non-spinning Rotorods	0.196	0.391	0.316	0.326
Mylar Samplers	0.250	0.224	0.121	0.206

The correlation between sampler types was obtained by computing the linear least squares through the averaged sampler data at each downwind distance. The accuracy of the least squares fit was measured by computing the correlation coefficients. A correlation coefficient above 0.9 is generally considered quite good, meaning that the straight-line fit accounts for 90 percent of the variance in the data. Because the data spans such a wide range in values, we choose also to examine the data logarithmically. This makes more of the data important rather than just its larger values. For the 6 variations we consider the results (with the first variable plotted along the logarithmic horizontal axis and the second variable plotted along the logarithmic vertical axis) as shown in Table 5.

The results show excellent correlation (0.935) between spinning and non-spinning Rotorod samplers. There is also a good correlation (0.812) between spinning Rotorod and Mylar samplers. Shewchuk, Wallace and Maybank (1991) reported a correlation coefficient of 0.656 when comparing Rotorod to a deposition sampler using chemical analyses. Trial 3, with an average correlation coefficient for all sampler comparisons, was 0.942 compared to 0.833 for Trial 1 and 0.752 for Trial 2. We believe this is an excellent correlation given two different types of samplers measuring different drift components.

Table 5. Statistical comparisons of sampler types; logarithmic least squares (with (a) slope of the line and (b) vertical intercept) and correlation coefficients. combined over all 3 trials.

Samplers	Logarithmic Least Squares	Correlation Coefficients
Spinning Rotorods (CFU-min/l) vs. Wagner Samplers (CFU-min/l)	0.535a 1.255b	0.779
Spinning Rotorods (CFU) vs. Non-spinning Rotorods (CFU)	0.987a 1.092b	0.935
Spinning Rotorods (CFU) vs. Mylar Samplers (CFU/sq cm)	1.469a -2.602b	0.812
Wagner Samplers (CFU) vs. Non-spinning Rotorods (CFU)	1.502a -0.123b	0.672
Wagner Samplers (CFU) vs. Mylar Samplers (CFU/sq cm)	1.851a -2.859b	0.590
Non-spinning Rotorods (CFU) vs. Mylar Samplers (CFU/sq cm)	1.396a -6.674b	0.877

Results of Drift Quantification (Task 2)

Drift, as expressed in dosage (Table 6) by colony forming units (CFU), was observed throughout the entire 3150 meter sampling line. Positive deposition was observed downwind to 1550 meters (Table 6), the maximum downwind extent of the deposition sampling. Table 7 presents downwind drift as a relative function indexed to the downwind edge of the treatment block. While deposition falls off rapidly with only 15 percent of the deposition remaining at 350 meters downwind, dosage as measured by Wagner samplers is still at 14 percent, 1550 meters downwind; and 3.13 percent, 3150 meters. Percent recoveries on both spinning and non-spinning Rotorods were more matched and at lover levels than those of the Wagner samplers. The rapid drop-off in drift beyond 900 meters is noticeable. The spinning Rotorod and Wagner dosage data are plotted in Figures 2-4. Drift, as expressed by deposition on Mylar samplers, is presented on Figures 5-7. The Rotorod and Mylar plotted data points represent an average of sampler pairs.

Table 6. Downwind recoveries of Bt by Rotorod dosage and Mylar samplers, average of 4 samplers at each location.

Downwind Distance (meters)	Dosage CFU minutes/liter of air			Deposition CFU/Sq. Cm.		
	TRIALS			TRIALS		
	1	2	3	1	2	3
0	1.7×10^7	5.0×10^7	4.9×10^7	2×10^7	1.4×10^8	8.9×10^7
350	1.4×10^7	5.3×10^6	1.5×10^7	4.4×10^6	3.3×10^6	1.8×10^7
475	3.4×10^6	N/D	4.5×10^6	4.4×10^5	4.1×10^5	2.8×10^6
900	2.7×10^6	1.5×10^6	4×10^6	2×10^5	1×10^6	2.3×10^6
1075	6.3×10^5	5.7×10^5	3.3×10^6	3.4×10^4	1.53×10^6	2.4×10^6
1550	2.6×10^5	3.9×10^5	1.7×10^6	6.5×10^3	1.6×10^5	1.4×10^6
1700	7×10^4	1.4×10^5	5.5×10^5		N/D	
2000	5.1×10^4	9.8×10^4	1.8×10^5		N/D	
2350	5.3×10^4	6.5×10^4	2.1×10^5		N/D	
3150	5.2×10^3	4.2×10^3	1.1×10^5		N/D	

N/D = no data
CFU = Colony Forming Units, colonies produced on agar plates.

Table 7. Mean recoveries averaged over the three trials as percent of recoveries at downwind edge of treatment block.

Distance (m)	Mylar (deposition)	Sampler Wagner (dosage)	Rotorod Spinning (dosage)	Rotorod Non-Spinning (impaction)
0	100.00	100.00	100.00	100.00
350	15.00	35.67	40.67	35.33
475	1.76	28.00	14.50	6.67
900	1.56	43.00	9.00	6.00
1075	1.40	8.00	4.00	3.67
1550	0.71	14.00	0.70	1.40
1700	---	3.67	0.57	0.24
2000	---	3.67	0.53	0.24
2350	---	5.67	0.27	0.23
3150	---	3.13	0.08	0.22

Figure 2. Trial 1, dosage downwind showing FSCBG predictions (solid line) compared to paired Rotorod (solid circle) and Wagner (open square).

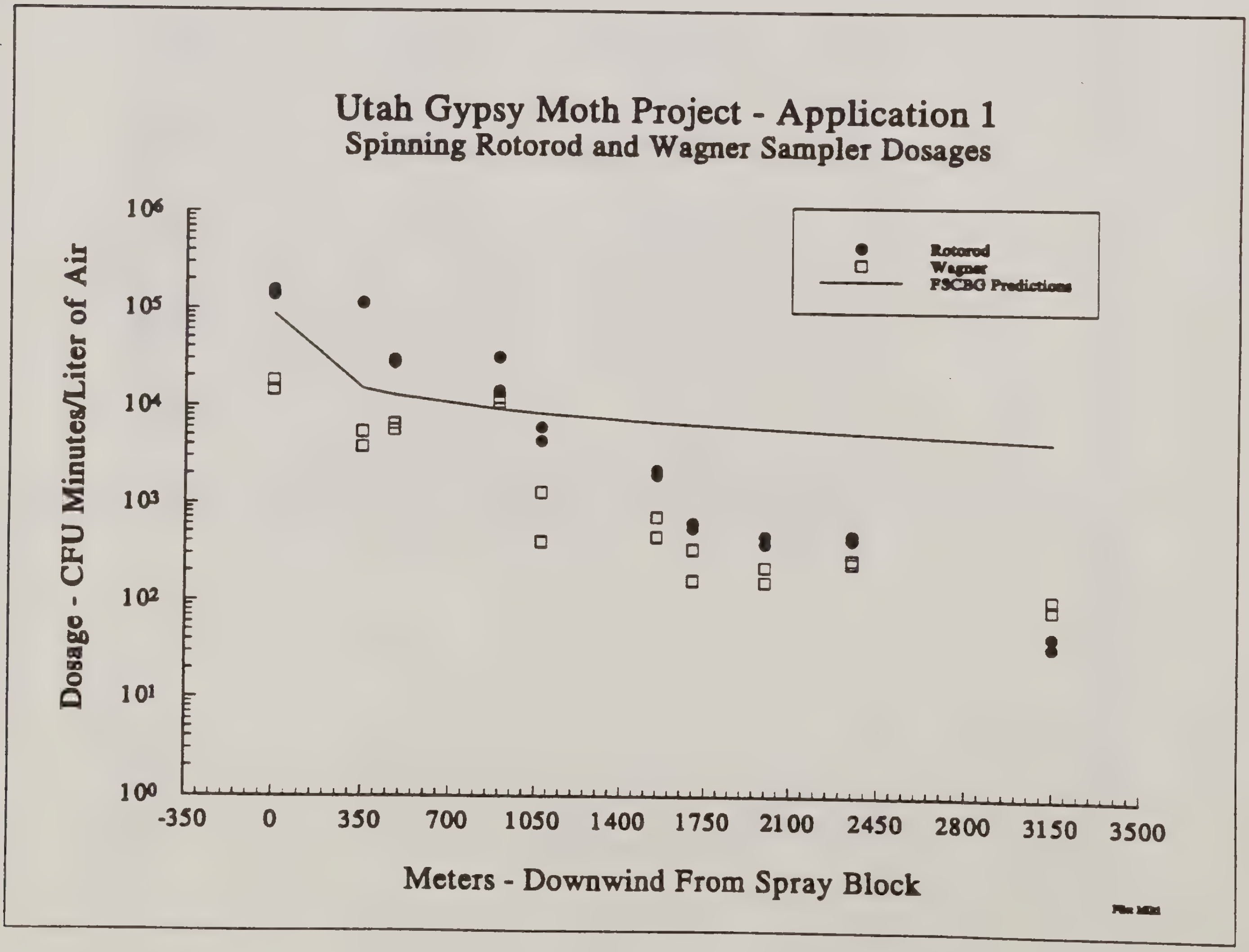


Figure 3. Trial 2, dosage downwind showing FSCBG predictions (solid line) compared to paired Rotorod (solid circle) and Wagner (open square).

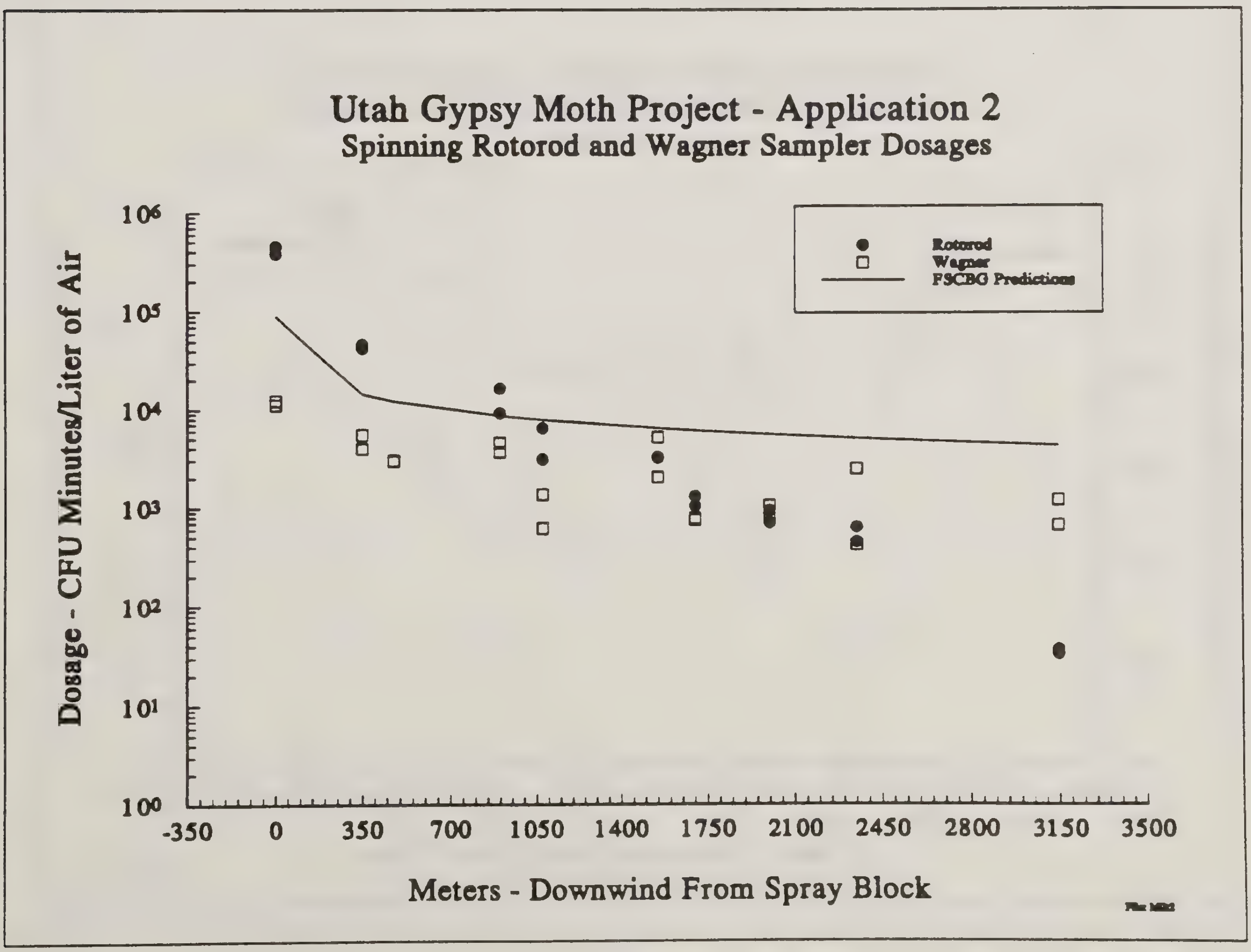


Figure 4. Trial 3, dosage downwind showing FSCBG predictions (solid line) compared to paired Rotorod (solid circle) and Wagner (open square).

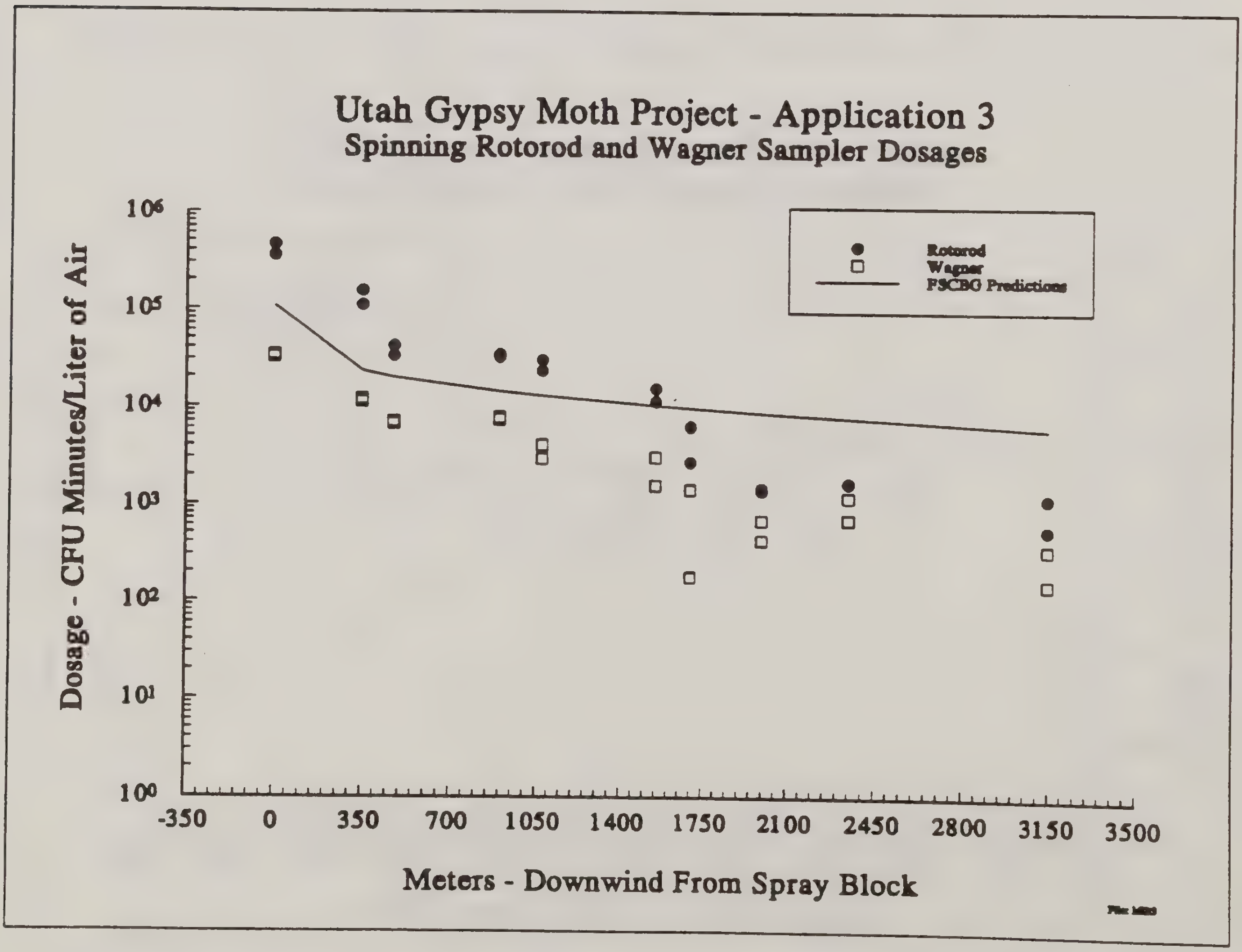


Figure 5. Trial 1, deposition downwind showing FSCBG predictions (solid line) compared to Mylar samplers (solid circle).

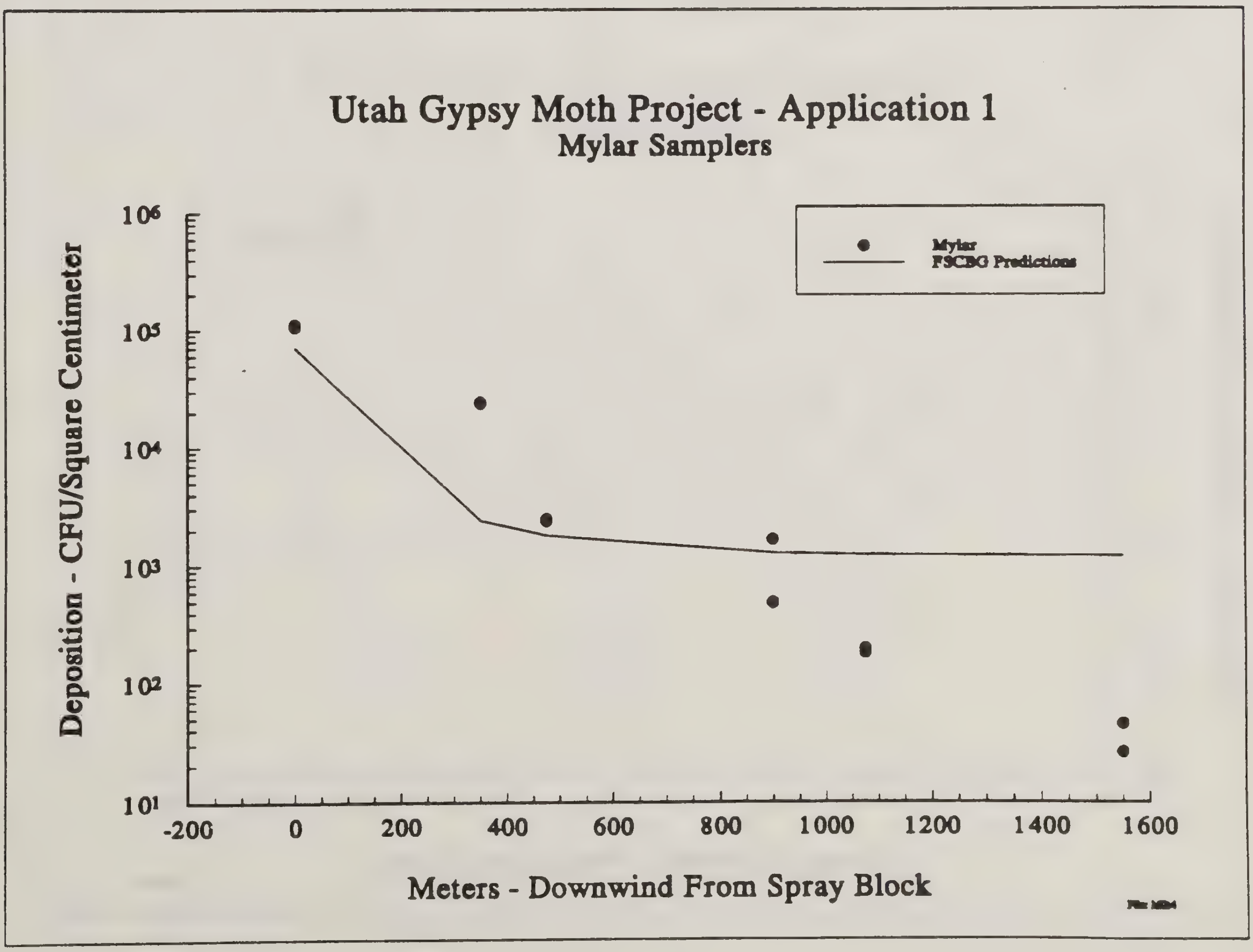


Figure 6. Trial 2, deposition downwind showing FSCBG predictions (solid line) compared to Mylar samplers (solid circle).

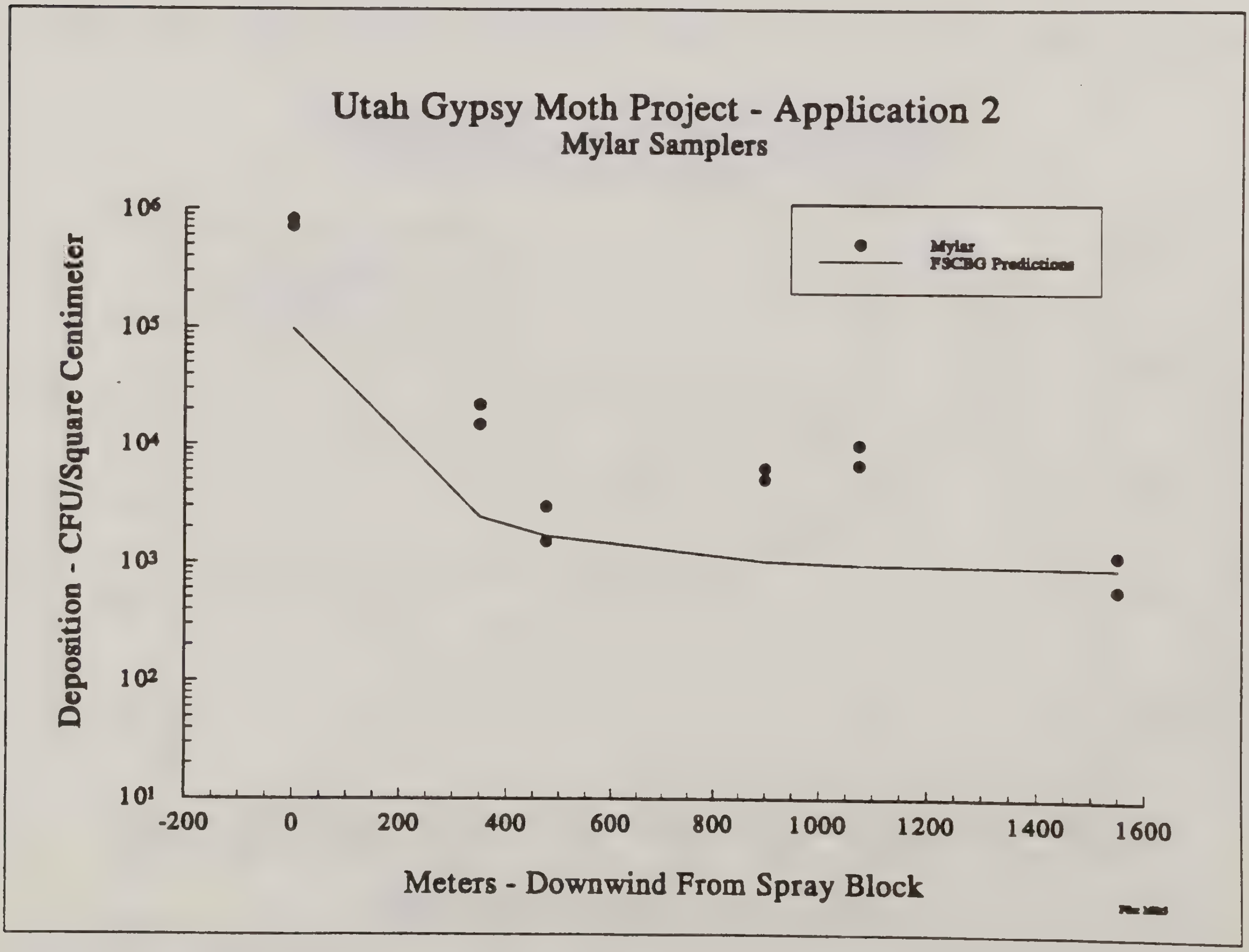
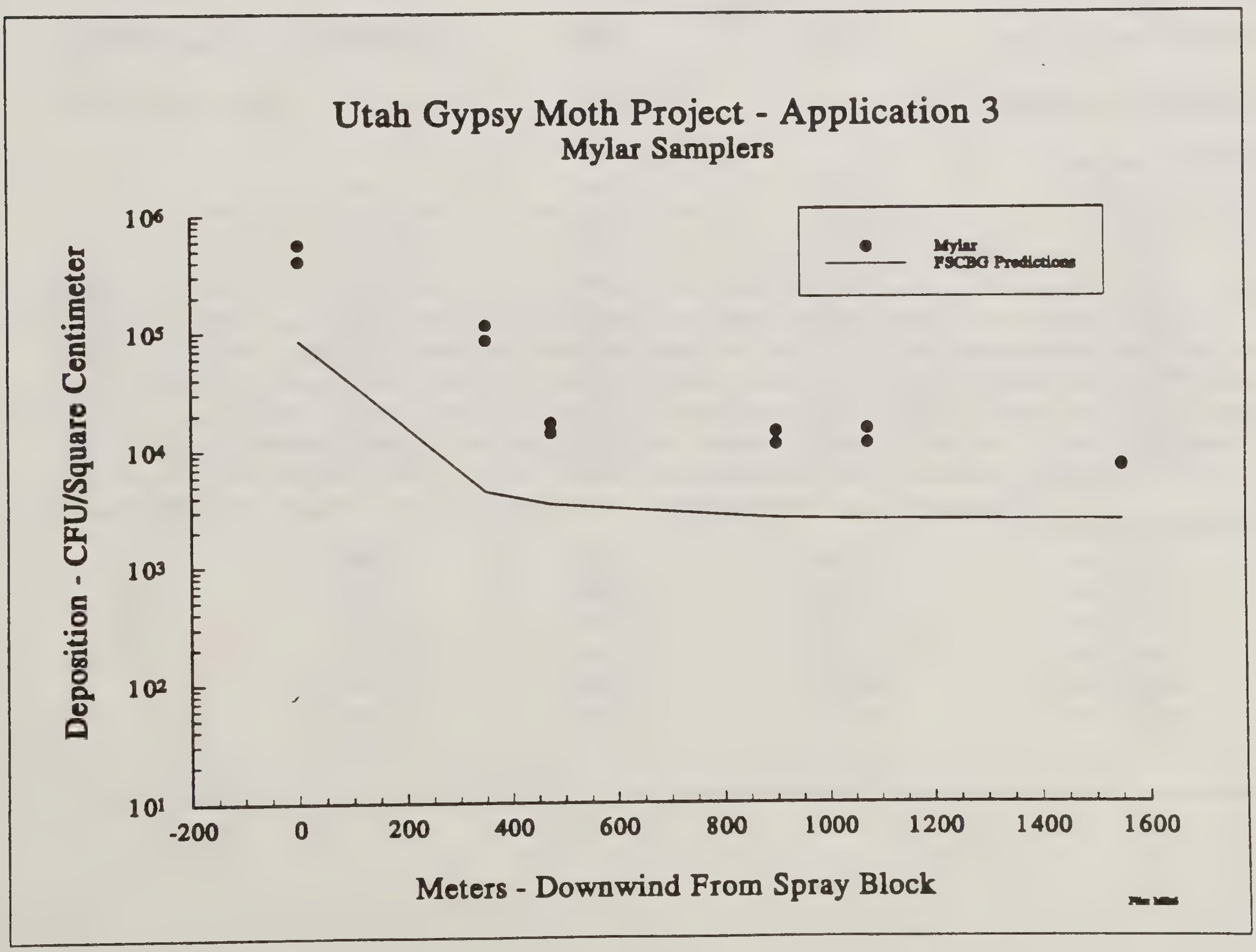


Figure 7. Trial 3, deposition downwind showing FSCBG predictions (solid line) compared to Mylar samplers (solid circle).



Results of FSCBG predictions (Task 3)

An extensive statistical analyses was conducted to evaluate FSCBG's performance against the data sets using the same equations in Task 1 analysis. The variability in the data between different sampler types and the undocumented complex atmospheric conditions existing in the canyon during the study, demonstrate some of the challenging difficulties in modeling aerial sprays.

In comparing standard deviations between sampler recoveries and FSCBG predictions (Table 8) one notes that FSCBG predictions do a good job of following the data downwind until the clouds dispersion and growth characteristics downwind prevent an accurate prediction of dosage/deposition. Then the statistics become worse.

Table 8. Relative standard deviations of FSCBG predictions at each downwind location compared to averaged sampler recoveries.

Dosage/Deposition	Trial 1	Trial 2	Trial 3	Combined
FSCBG Dosage	0.665	0.575	0.518	0.589
FSCBG Deposition	0.606	0.620	0.693	0.641
Dosage/Distance				
FSCBG Dosage				
0.0 m	0.080	0.015	0.001	
350.0 m	0.003	0.000	0.067	
475.0 m	0.000	0.367	0.011	
900.0 m	0.067	0.009	0.003	
1075.0 m	0.393	0.346	0.022	
1550.0 m	0.528	0.106	0.098	
1700.0 m	0.797	0.533	0.548	
2000.0 m	0.829	0.531	0.665	
2350.0 m	0.779	0.555	0.523	
3150.0 m	0.946	0.847	0.750	
FSCBG Deposition				
0.0 m	0.047	0.603	0.488	
350.0 m	0.673	0.582	0.837	
475.0 m	0.022	0.014	0.403	
900.0 m	0.030	0.481	0.438	
1075.0 m	0.539	0.626	0.463	
1550.0 m	0.893	0.001	0.249	

Furthering the statistical analysis of FSCBG the correlation coefficients of FSCBG predictions (Table 9) to sampler recoveries, in some cases, are as high as those that compare sampler types.

Table 9. Statistical comparisons of sampler recoveries to FSCBG predictions; logarithmic least squares (with (a) slope of the line and (b) vertical intercept) and correlation coefficients. Combined over all three trials.

Samplers	Logarithmic Least Squares	Correlation Coefficients
Spinning Rotorods (CFU-min/l)		
vs.	0.296 a	
FSCBG Dosage (CFU/min/l)	2.928 b	0.736
Wagner Samplers (CFU-min/l)		
vs.	0.442 a	
FSCBG Dosage (CFU-min/l)	2.593 b	0.607
Mylar Samplers (CFU-min/l)		
vs.	0.481 a	
FSCBG Deposition (CFU/sq cm)	1.642 b	0.630

Data in Table 10 for Trial 1 the FSCBG prediction shows a value of 1.608. This implies that the prediction over predicts the average of the data by 60.8 percent. The larger predicted values are evident further downwind, as can be seen from Figures 2-7. Dosage predictions, however, are quite good in Trials 2 and 3. The deposition predictions show clearly that FSCBG under predicts the levels found downwind of the edge of the spray block. Overall, the agreement can be argued to be quite good, given the terrain and complex atmospheric conditions of mountains that were not quantitated in this study.

Table 10. Logarithmic Least square straight line slope analyses between average field data values at each downwind location to FSCBG predictions.

Predictions	Logarithmic Least Squares Straight Line Slope		
	Trial 1	Trial 2	Trial 3
Dosage	1.608	1.277	0.906
Deposition	0.619	0.126	0.172

Conclusions

The USDA Forest Service in cooperation with the U.S. Army has developed and evaluated FSCBG a computer model that predicts the dispersion and deposition of aerial sprays. Over the past 20 years the model has been evaluated under a variety of terrain conditions and improved as data and user needs have developed. The model is user-friendly operable on a personal computer and contains data bases of aircraft and spray nozzle atomization. A study was conducted in Utah during 1991 to evaluate samplers, quantitate drift, and compare FSCBG predictions to field data. The 4 types of samplers used in this study were effective in their reproducibility in collecting samples of Bt spray provided for the quantification of drift downwind from the 834 hectare treatment area. Results demonstrated the remarkable effectiveness of the model to predict deposition and dosage of the biopesticide aerosol from the treatment area downwind to 3150 meters. Statistical analyses supports the performance of samplers used in the study; and the accuracy and predictability of the model within the limitations of the state-of-the art field sampling technology and characterization of the atmosphere. FSCBG provides a vehicle for reducing the need for costly field tests; and for calculating buffer zone and drift potential of pesticides. Encouraged by these excellent results from the 1991 study, funding was extended to continue the off-site drift study in 1992 to provide an expanded data base and monitoring drift at greater distances.

RECOMMENDATIONS

There are several challenges to designing and conducting computer model evaluation studies. Attention to the selection and use of samplers is critical and we recommend that paired and duplicate sampling be used for statistical quantification of sampler performance. Characterization of the atmosphere particularly in complex terrain is another challenge to obtain sufficient number of surface and upper air measurements. In complex terrain we recommend at least three 2-meter surface observation stations for each 1500 kilometers of downwind sampling and upper air measurements from surface up to high terrain features. The favorable FSCBG predictions for complex terrain noted on this study leads us to recommend future studies with improved meteorological observations in forest terrain while concurrently pursuing a complex terrain model as proposed by Ekblad et al. (1991).

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